A UNITED STATES DEPARTMENT OF COMMERCE PUBLICATION

NOAA Technical Report ERL 239-APCL 23

U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
Environmental Research Laboratories

(NASA-CR-133400) A THREE-STATION LIGHTNING DETECTION SYSTEM (National Oceanic and Atmospheric Administration) 46 p MF $0.95; SOD HC $0.75 CSCL 14B

N73-27382

Unclas

G3/14 09302

A Three-Station Lightning Detection System

LOTHAR H. RUHNKE

BOULDER, COLO.
JULY 1972

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For sale by the Superintendent of Documents, U. S. Government Printing Office, Washington, D. C. 20402

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A THREE-STATION LIGHTNING DETECTION SYSTEM

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A three-station network is described which senses magnetic and electric fields of lightning. Directional and distance information derived from the data are used to redundantly determine lightning position. This redundancy is used to correct consistent propagation errors. A comparison is made of the relative accuracy of VLF direction finders with a newer method to determine distance to and location of lightning by the ratio of magnetic-to-electric field as observed at 400 Hz. It was found that VLF direction finders can determine lightning positions with only one-half the accuracy of the method that uses the ratio of magnetic-to-electric field.

1. INTRODUCTION

Lightning positioning systems have been in use for a long time; however, data on their accuracy are difficult to obtain because of the complexity of the physical problem of wave propagation as well as technological problems that must be overcome to verify indicated lightning positions. In addition, the location of a lightning as such is difficult to define, because of its complex space and time structure. Several methods are used to determine the position. Most commonly used are direction finders that use loop antennas to sense the magnetic field radiated from a lightning. The position can be found by having two or more receiving stations and by using triangulation methods. For thunderstorms less than 100 km away, Ruhnke (1971 has recently proposed to use the ratio of magnetic field to electric field as an indicator for distance. The amplitude of the electric field from a lightning can also be used as an indicator for distance, if we assume that the dipole moment does not change among individual strokes. The latter two methods, in conjunction with direction finders, lead to positioning systems that need only one observation station.

This study tested several of these methods and compared their relative accuracy. The inherent difficulty of such a study is that no data on the actual position of lightning exists; therefore, conclusions about the accuracy can only be derived by comparisons of systems, each having its individual error source. The assumption is then made that no error exists if most or all of the systems indicate lightning at the same location.

For this, three stations spaced in a triangle about 10 km on a side were equipped with crossed loop antennas to sense the magnitude of the magnetic field and the direction to the strokes. These stations also had horizontal wire antennas to sense the magnitude of the electric field. The position of a number of lightning was then calculated from directional data using three baselines, from data of the ratios of the magnetic to electric field (H/E) at three stations, and from the magnitude of the electric field at three stations. For each lightning a set of nine positions is obtained and can be used in an error analysis. A tenth set of data was evaluated from an operational two-station direction finder using crossed loop antennas but having different electronics and different observation frequencies. This data set was included to assess the importance of errors that are introduced by electronic equipment rather than propagation and lightning characteristics.

2. INSTRUMENTATION

At each of the three observation stations identical equipment was used. For the magnetic pickup, crossed loop antennas were used as previously described (Ruhnke, 1971). This reference also describes the horizontal wire antenna to sense the electric field, as well as filters, amplifiers, and pulse-forming networks. The equipment differs from that previously described only by different output signals. Figure 1 is a block diagram that facilitates the understanding of the detailed diagram in figure 2. Voltages from the crossed loop antennas are filtered by a 400-Hz filter and amplified by factors of 10, 100, or 1000 by adjustable amplifiers. Then the signal is processed by precision full-wave rectifiers and peak voltage detectors. The outputs are labeled HX for the

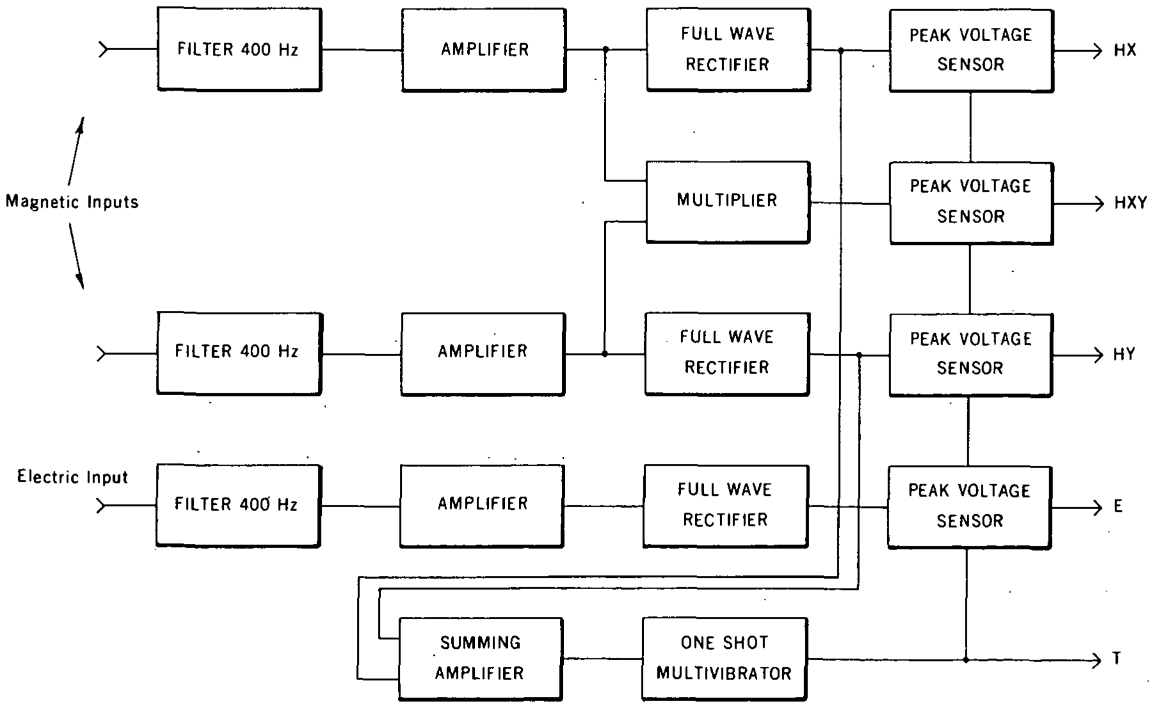

Figure 1. Block diagram of receiving station.

east-west, and HY for the north-south component of the magnetic field. The voltages of both crossed loop antennas are also multiplied with each other after additional amplification, and the peak voltage of the product is available at the output as signal HXY. This pulse is necessary to sense whether both loop antennas have the same or opposite polarity signals, because the sharp filter and the full-wave rectifier loses the information on polarity. The rectified loop antenna signals are added in a summing amplifier and trigger a one-shot multivibrator. This trigger signal T programs the peak voltage modules. For 1 sec the output of the peak voltage circuit displays the peak voltage.

The signal from the long wire antenna is similarly filtered, amplified, and rectified. The output of its peak voltage circuit is labeled E. Four channel strip chart recorders recorded the output voltages at all three sites at 1 mm/sec. For this study, all 12 values of each lightning were manually read from the chart paper and transferred to punch cards for computer analysis. The time to 1 sec and the date of each lightning was also kept on punch cards. This method of analysis is nonpractical for fast read-out of information on lightning location.

The design of the instrumentation took into account the need for rapid information analysis. The output signals can be scanned by analog-to-digital converters, and real-time computation by moderately sized digital computers can give information on lightning position as well as probable accuracy of the data. On an experimental basis a scanner and digital voltmeter, along with the programmable desk calculator (Model HP 9100B of Hewlett Packard), calculated lightning position, printed it with

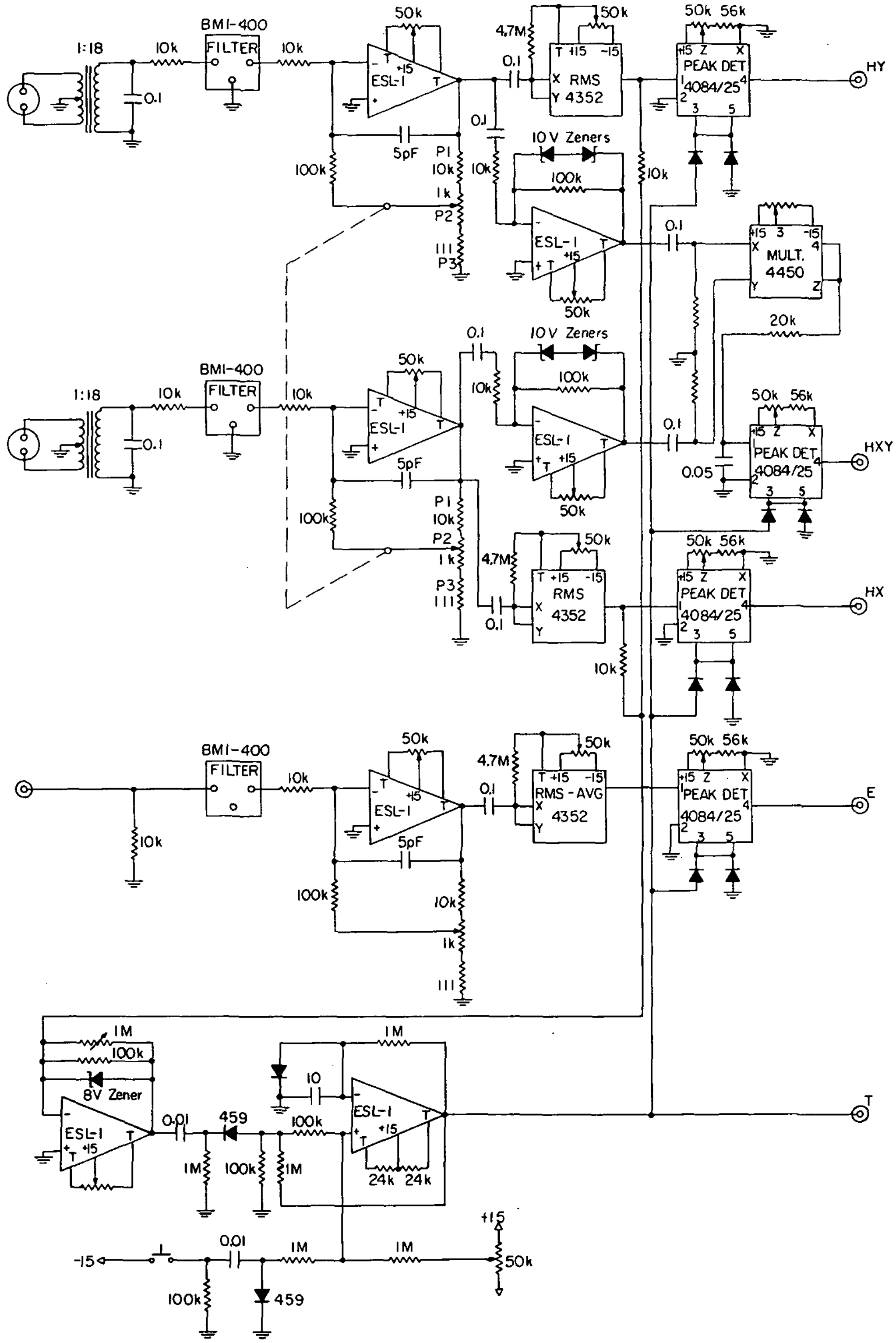

Figure 2. Detailed diagram of receiver instrumentation.

time on a digital printer, and plotted lightning position on a map using an x-y plotter. Computational time was 7 sec including printing and plotting.

Within 1 sec of the start of a lightning signal, the instrument puts out voltages proportional to the peak amplitudes. The maximum voltage before instrument saturation is 10 V. Only positive voltages are sensed. Transients, zero drift, and nonlinear effects do not produce errors of more than 10 mV. An exception was station 3, where 60 Hz noise was picked up by the instrument and 160 mV appeared at the output of the north-south component of the magnetic field. This error voltage was eliminated by mounting the instrument in a different location within the shelter. However, the lightning data discussed in this report, contain this error that somewhat decreased the reliability of station 3.

3. THEORETICAL CONSIDERATIONS

3.1 Calculation of Lightning Position

Assume a rectangular coordinate system centered at station 1 with the x-axis toward the east and the y-axis toward the north. Assume further that the coordinates of station 2 are X(2), Y(2), and for station 3, X(3) and Y(3). The position of lightning number M can be expressed by using the direction to the lightning from two stations together with the station coordinates. The direction to a lightning at station 1 can be expressed by the tangent XM(1,M) of the angle from the x-axis:

$$XM\ (1,M) = HY1/HX1\ . \tag{1}$$

The polarity of this tangent is decided by the absence or presence of a pulse at HXY1, namely, whether the product at HX1 and HY1 is positive. If a positive pulse appears at HXY1, the tangent is negative. In FORTRAN notations this is expressed by

$$\text{IF (HXY1. GT.0.) XM (1,M) = -XM (1,M)} . \quad (2)$$

Similar notations are used for the direction to lightning M from stations 2 and 3.

The position of a lightning using station 1 and 2 as baseline is expressed by the coordinates X1(M) and Y1(M):

$$X1(M) = (Y(2) - XM(2,M) * X(2))/(XM(1,M) - XM (2,M)), \quad (3)$$

$$Y1(M) = X1(M) * XM(1,M) \quad . \quad (4)$$

Similar equations apply for the positions calculated from the other two baselines. Directional data will therefore produce a set of three positions for every lightning. The area of the triangle formed by these three positions can be used to estimate the accuracy, with the assumption that the locating error is zero if the triangle area is zero. This assumption is reasonable, yet not totally convincing. The area F of this triangle can be calculated from

$$F = (X1\ (M) * Y2\ (M) - X2\ (M) * Y1\ (M) + X1\ (M) * Y3\ (M) - X3\ (M) * Y1\ (m) + X2\ (M) * Y3(M) - X3\ (M) * Y2\ (M))/2. \quad (5)$$

This area F not only can be used to judge the reliability of a particular position calculation but also several statistics can be performed on this number which will assess this system's accuracy relative to other systems.

In particular, the average area $\overline{F}$ will give an indicatin of random errors and give a means of finding consistent errors in the system, as will be shown later.

An additional set of three lightning positions can be obtained from the ratio of the magnetic-to-electric field (H/E) at each of the three stations together with directional information (Ruhnke, 1971). With an observation frequency of 400 Hz, as used in our equipment, H/E increases approximately linearly with distance D between 3 km and 80 km,

$$D1\ (M) = T1 * SQRT(HX1 * HX1 + HY1 * HY1)\ /E1 \quad . \tag{6}$$

The factor T1 depends on antenna length, amplifier gains, and loop antenna size and is best determined empirically so that the average area $\overline{F}$, by using data from three stations, is a minimum. One obtains the x and y coordinates at station 1 by

$$X1\ (M) = HX1 * T1/E1, \tag{7}$$

$$Y1\ (M) = X1\ (M) * XM\ (1,M)\ . \tag{8}$$

The polarity of the x-coordinate must be determined independently, since our direction finders have an inherent 180° ambiguity. In principle, there is no difficulty in eliminating this ambiguity by comparing the polarity of the electric signal with that of the magnetic signal. For our study, data from the other two stations were used to eliminate the 180° ambiguity.

3.2 Error Analysis

Several error sources in lightning positioning systems can be identified. Two basic philosophies can be used to investigate and eliminate such error sources. First, one can study the physics of lightning and the physics of its propagation and make measurements pertinent to deviations from idealized or standardized conditions. Such measurements can then be used to correct the lightning data. Second, one can look statistically at the data. Because we have measurements from which the lightning position can be determined in more than one way, one can use this overdetermination to find statistical correction terms.

A lightning is an electrical discharge in the atmosphere and has a physical length that often is comparable with the distance to the observation point. The approximation of a lightning by the position of a point on the ground already introduces errors because the measuring method uses possibly a different approximation scheme than the method to verify the result. For instance, the sensing of the magnetic fields produced by a branched lightning with horizontal components inside the thundercloud will yield an average direction to a lightning. This direction is different than the direction obtained for the same lightning by optical observation of the visible part beneath the cloud. Another direction may be obtained by detecting the location where the lightning made contact with the ground. This error, or uncertainty in position, usually will be less than the horizontal extent of the lightning. A positioning error of 1 km from the source must be expected; therefore, any system judged to be accurate in positioning lightning to within 1 km must be considered excellent.

Limiting the error analysis to lightning that are approximated as point sources and sensed by their electric and magnetic field, one must now differentiate between (1) distortion produced by the propagation path, namely, such distortions that apply to all lightning at one locality like finite ground conductivity, secondary radiator, and inhomogeneities in the propagation path, and (2) between height above ground and orientation in space of individual elementary lightning dipoles. While the first category is fixed in time and space such that compensations for it can be calculated or empirically applied if the cause for such distortions can be assessed, the second category is random from one lightning to the next and can only be reduced by using less affected measurement parameters.

Additional errors are introduced by the instrumentation. A difference in gain of the loop antennas will cause directional error, as will inaccuracies in positioning the loop antennas. The coordinates of the observation station must also be accurate. Noise in the electronics, nonlinearities, and drifts in the amplifiers will introduce errors. However, these are accessible to investigation, and periodic checks and calibration can minimize instrumental errors of a well-designed system.

Other systems errors are those inherent in triangulation systems: the length of the baseline and the direction to a lightning in relation to baseline direction. In particular for lightning near baseline direction, the positioning error becomes very large if small angular errors are made. Assume the origin of the coordinate system to be at midpoint of a 10-km baseline, which extends along the x-axis. Figure 3 shows the distribution of maximum positioning error E_1 in kilometers for a directional error of 1° at each station.

For distances larger than the baseline, this error E_1 increases approximately with the square of the distance and it approaches high values when the lightning is near baseline direction. The plot in figure

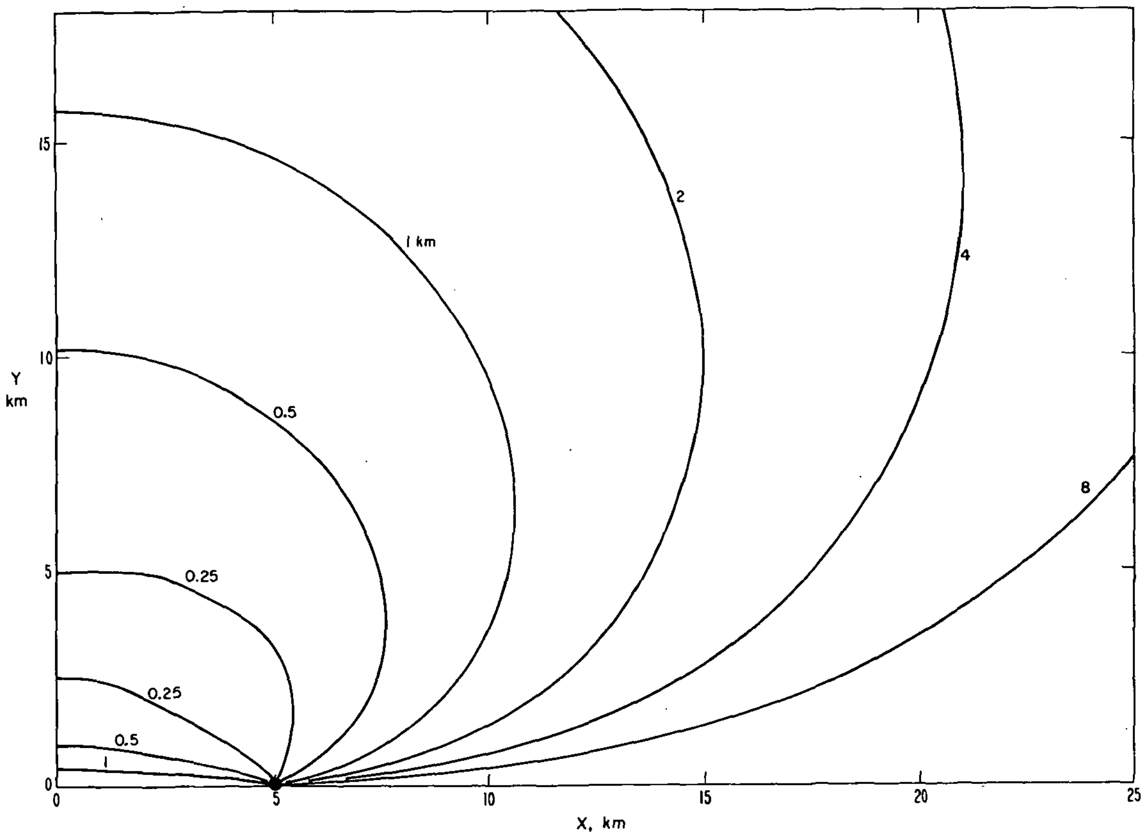

Figure 3. Magnitude of positioning error for direction finders with 10 km baseline and 1° azimuthal error at each station.

3 is based on the following formula, where D_1 and D_2 are the distances to the lightning from stations 1 and 2, a is the baseline length, and y the lightning coordinate perpendicular to baseline direction

$$E_1 = \frac{\pi}{180} \frac{D_1 \cdot D_2}{y \cdot a} (D_1 + D_2) \quad . \tag{9}$$

A similar analysis is possible if the position of a lightning is calculated by using distances to lightning at two stations. Of more importance to this study, however, is the position error, if the location is determined by direction and distance from one station only. Assuming that errors caused by uncertainties in direction are equal in magnitude to errors caused by uncertainties in distance, the positioning error E_2 is obtained similar to (9) for directional uncertainties of 1°:

$$E_2 = \frac{\pi}{180} \cdot \sqrt{2} \cdot D \quad . \tag{10}$$

E_2 is always smaller than E_1, which encourages the development of single-station systems for locating lightning. How well the assumption -- that uncertainties in determining distance from one station are equal in magnitude to uncertainties in determining direction to lightning -- holds is subject to experiments.

The next error considered is random noise from either external sources or from within the electronics. At station 3 the receiver electronics was accidentally mounted in a rack near a strong power supply that induced noise into the y-component of the magnetic field. Since such error signals can appear to some extent at each location, it is advantageous to consider compensating for this error. This is possible, to some degree, if the noise source is steady and if noise on the average increases the output signal. The lightning signal S after the input filters is quasi-sinusoidal and has the form

$$S = S_0 \sin (\omega t) \quad , \tag{11}$$

with S_0 being the amplitude. Similarily the noise signal N has the form

$$N = N_0 \sin (\omega t + \emptyset) \quad , \tag{12}$$

where $\emptyset$ is an arbitrary phase angle and N_0 the amplitude of the noise signal. The output of the lightning detector is proportional to the amplitude of the sum of noise and lightning signal. Depending on the phase angle of the noise signal, the output signal either increases or decreases. On the average, the amplitude of the output signal S' is approximately given by

$$S'^2 = N_0^2 + S_0^2 \quad . \tag{13}$$

This formula can correct the output signal. The amplitude of the noise signal can easily be determined by manually triggering the peak voltage sensing circuit.

When more than two stations are used as direction finders, it is possible to detect from a sufficient number of lightning whether the direction finders are properly aligned. Suppose that a lightning from direction α is received by one station that is β degree's misaligned. The indicated angle γ relates to α and β by

$$\tan \gamma = \frac{\tan \alpha + \tan \beta}{1 - \tan \alpha \cdot \tan \beta}, \tag{14}$$

Such a misalignment will affect the area of the triangle computed from the positions of the lightning determined from directions from three stations. The average of such an area computed from many lightning incidents will also be affected. One can assume with good reason that this average area is a minimum for a 0° misalignment error. A calculation of the average area as a function of β will readily indicate if misalignment of any of the antennas is evident. In the experiment performed for this study, no such misalignment could be detected. This was as we expected because during installation the antennas were very carefully aligned.

There are several error sources that lead to consistent directional changes and which are difficult to eliminate after the system is installed. These sources are associated with inhomogenieties of the propagation path; with permeable materials of nearby manmade structures, like steel frame buildings or railroad tracks that at very low frequencies influence the magnetic field of a lightning signal; and with secondary radiators near the receiving site. To this category of errors also belong differences of antenna sensitivity between both crossed loop antennas as well as differences in the gain in the electronics of the two channels that process the crossed loop antenna signals. The effect of all these error sources is that certain magnetic field components are distorted. That means that the magnetic field component in direction α of a lightning from an arbitrary direction is increased by a factor M.

M and α are two numbers that characterize a single disturbance. For this case the x component HX as well as the y-component HY of the magnetic field is influenced. The disturbed values HX' and HY' can be expressed by

$$HX' = HX \cdot A + HY \cdot B, \tag{15}$$

$$HY' = HX \cdot B + HY \cdot C. \tag{16}$$

The constants A, B, and C depend on the two constants M and α :

$$\begin{aligned} A &= \sin^2 \alpha + M \cos^2 \alpha \ , \\ B &= (M-1) \sin \alpha \cos \alpha \ , \\ C &= M \sin^2 \alpha + \cos^2 \alpha \ . \end{aligned} \tag{17}$$

When M and α are known, (15) and (16) can be inverted to obtain the undistorted magnetic field components Hx and Hy,

$$HX = HX' \cdot A' + HY' \cdot B' \ , \tag{18}$$

$$HY = HX' \cdot B' + HY' \cdot C' \ . \tag{19}$$

For the constants A', B', and C', one finds

$$\begin{aligned} A' &= \sin^2 \alpha + \frac{1}{M} \cos^2 \alpha \ , \\ B' &= (\frac{1}{M} - 1) \sin \alpha \cos \alpha \ , \\ C' &= \frac{1}{M} \sin^2 \alpha + \cos^2 \alpha \ . \end{aligned} \tag{20}$$

In general, distortions do not occur in only one direction but are distributed as a function of α. If $M(\alpha)$ is known, then the three parameters in (17) can be determined

$$A = \frac{1}{\pi} \int_0^{2\pi} M(\alpha) \cos^2 \alpha \, d\alpha \ , \tag{21}$$

$$B = \frac{1}{\pi} \int_0^{2\pi} M(\alpha) \sin \alpha \cos \alpha \, d\alpha \ , \tag{22}$$

$$C = \frac{1}{\pi} \int_0^{2\pi} M(\alpha) \sin^2 \alpha \, d\alpha \ . \tag{23}$$

The constants for the inverted equations (18) and (19) are

$$A' = \frac{C}{AC - B^2} \ , \tag{24}$$

$$B' = \frac{-B}{AC - B^2} \ , \tag{25}$$

$$C' = \frac{A}{AC - B^2} \ . \tag{26}$$

From a practical point of view, it is impossible to determine $M(\alpha)$ as a continuous function. A, B, and C are best determined by experiment. As an error function, again the average area $\overline{F}$ of all triangles can be used as determined by directions to a number of lightnings from three stations. A computer program can search for the optimum values of A, B, and C which give the smallest average area $\overline{F}$.

With this last procedure any other possibilities of compensating for consistent errors in lightning direction finder systems seems to end. Still remaining are random errors which depend in magnitude on the type of measured parameters as well as on the variability of lightning characteristics. The experiment was aimed to derive a measure of this random error for the particular measurement system described in this report.

4. EXPERIMENTS

During the summer of 1971, the equipment described in this report was installed at three sites at Kennedy Space Center, Florida. Station 1 was on top of a four-story building with the approximate coordinates 28° 31' 26" N and 80° 38' 52" W. This station was used as the origin of a rectangular coordinate system in which the positive x-axis and y-axis point east and north, respectively. In this system, station 2 had the coordinates X(2) = -3.80 km and Y(2) = 11.32 km. Station 3 was located at X(3) = 7.00 km and Y(3) = 1.04 km. Several thunderstorms were recorded between June 25 and July 8, 1971, of which a storm period on July 2, 1971, between 15:30 LST and 18:00 LST was analyzed with particular care. During this time each lightning incident that produced a signal at all three stations was used for the data base. About 20 percent of all lightning signals were either too weak to trigger all three stations or occurred within less than 1 sec of each other, so that the two independent lightnings could not be differentiated. The data base consists of 268 lightning incidents and is tabulated in table A1 (see appendix). Time was recorded to within 1 sec in column 1. The data columns 2 to 13 are marked HX, HXY, HY, and E to denote the components of the magnetic field, the polarity signal, and the magnitude of the electric field from all three stations. Columns 14 to 17 are magnetic field data from the KSC operational lightning locating system with its two stations located very close to our stations 1 and 2. X_1, X_2, Y_1, Y_2 denotes the x and y components of the magnetic field. The last column is a counter to help to identify individual lightning strokes. The values in data column 2 to 13 are output voltages in units of 20 mV. The resolution of the chart paper recordings from which the data were taken is ± 50 mV; which means that the last digit already includes a considerable uncertainty. The sensitivity of the electric field channel at station 1 was decreased at 16:28 LST by a factor of 10. All data of E1 from lightning 124 to 268 are therefore in units of 200 mV. Full scale and voltages higher than full scale are denoted by 500. Columns 14 to 17 are readings taken from a digital printer and are in units of 10 mV.

On July 2, 1971, the Cape Kennedy Space Center area in Florida had typical thunderstorm conditions for this time of the year. On the synoptic chart for that day a long cold front extended from Texas, through Georgia, and North Carolina up to Labrador moving slowly towards Florida. The Showalter Stability Index from Cape Kennedy radiosonde data at 2:00 p.m. LST was zero, indicating increasing chances of thunderstorms. Winds were variable at about 10 mph from the SW. After a clear morning, cumulus clouds began developing at 10:00 LST in the west. Over the water and east of station 3, the sky stayed clear until after the measuring period. During the measuring period, a large area west of station 3 was covered with clouds. Intermittent heavy rain was observed at stations 1 and 2 with lightning and thunder occurring about three times per minute. Figure 4 is a graph of the number of lightnings per minute during the observation period averaged over 5-min intervals.

Figures 5 to 17 show lightning positions on a 100 km by 100 km map. Station 1 is in the center. All three stations are connected by a solid line to show the observational network. In figure 5, directional data

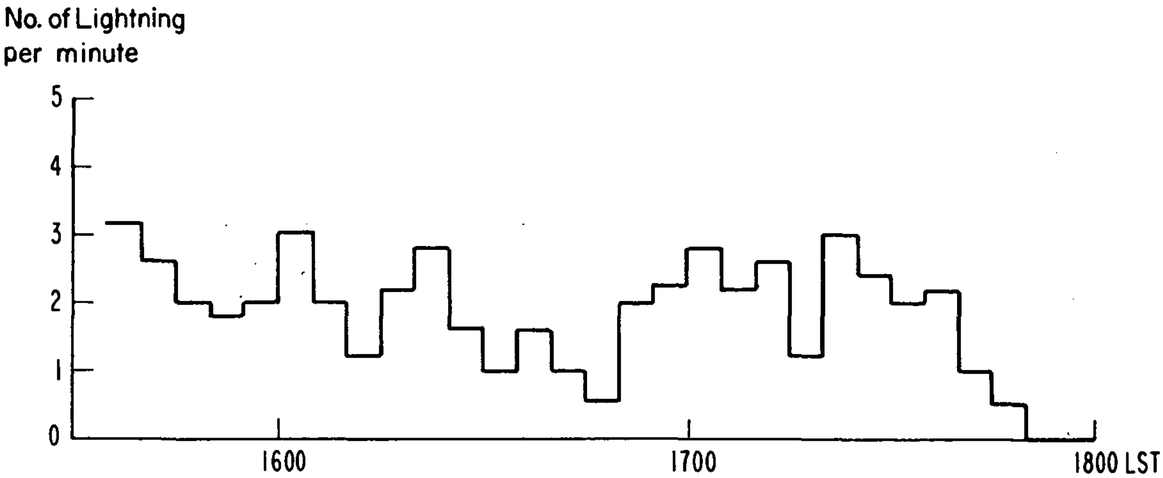

Figure 4. Lightning frequency during observation period on July 2, 1971.

from stations 1 and 2 were used to calculate lightning positions. No corrections were applied to the data, and all positions outside the 100 km by 100 km were as shown on the borderline. Two thunderstorm areas can be recognized. The cluster of lightning 10 km west of station 2 occurred mainly between 1530 and 1645 LST. The storm which was 30 km southwest of station 1 occurred between 1645 and 1800 LST. In figure 6 the same lightning positions are shown from directional data of stations 2 and 3. The first storm now appears in a wide scatter up to 20 km west and north of station 2, while the second storm now is fairly concentrated at 18 km southwest of station 2. For the earlier storm, 10 percent of the lightnings were so close to the baseline direction of stations 2 and 3 that they appeared in the wrong quadrant. Finally in figure 7 directional data from sites 1 and 3 are used for calculating

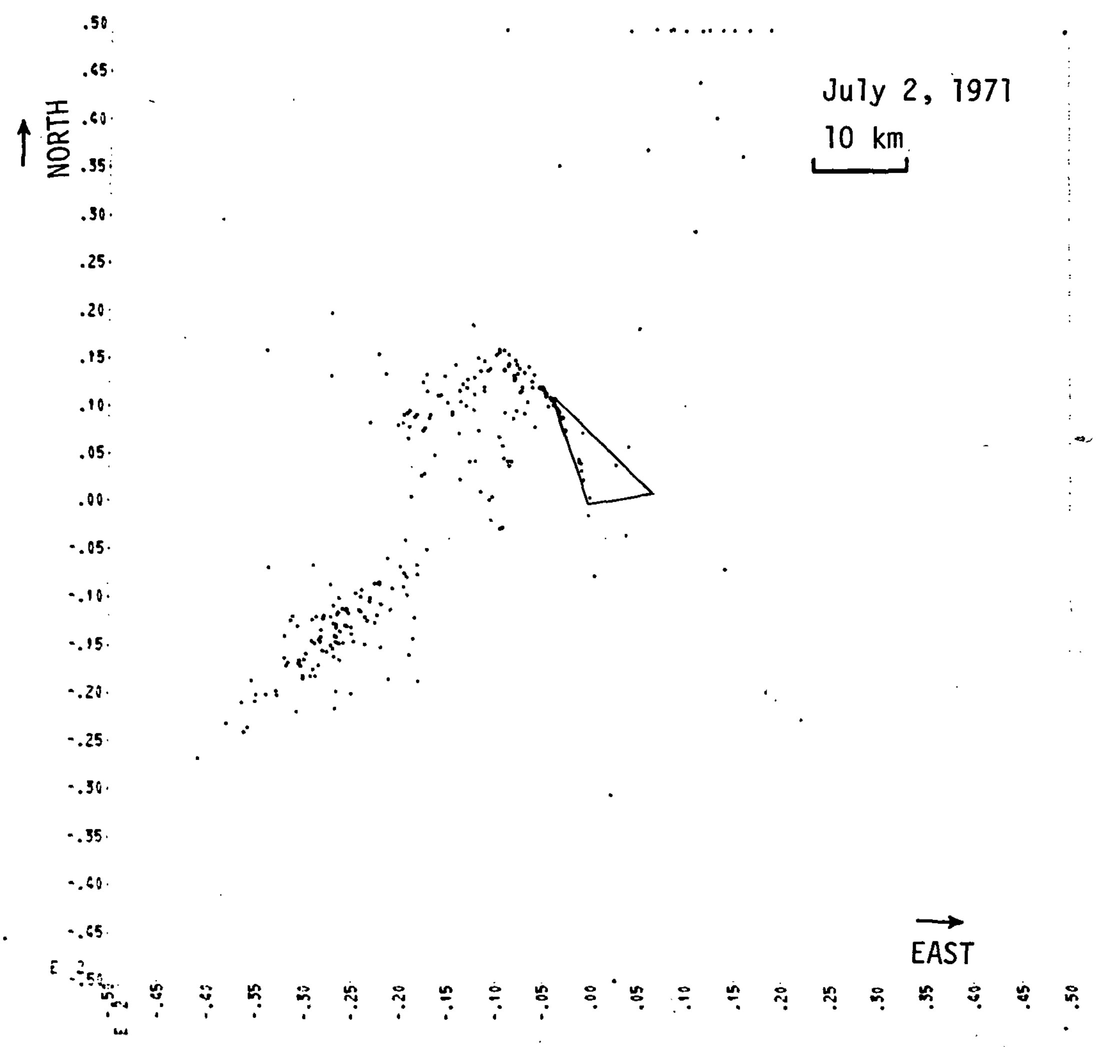

Figure 5. Lightning positions from uncorrected directional data from stations 1 and 2.

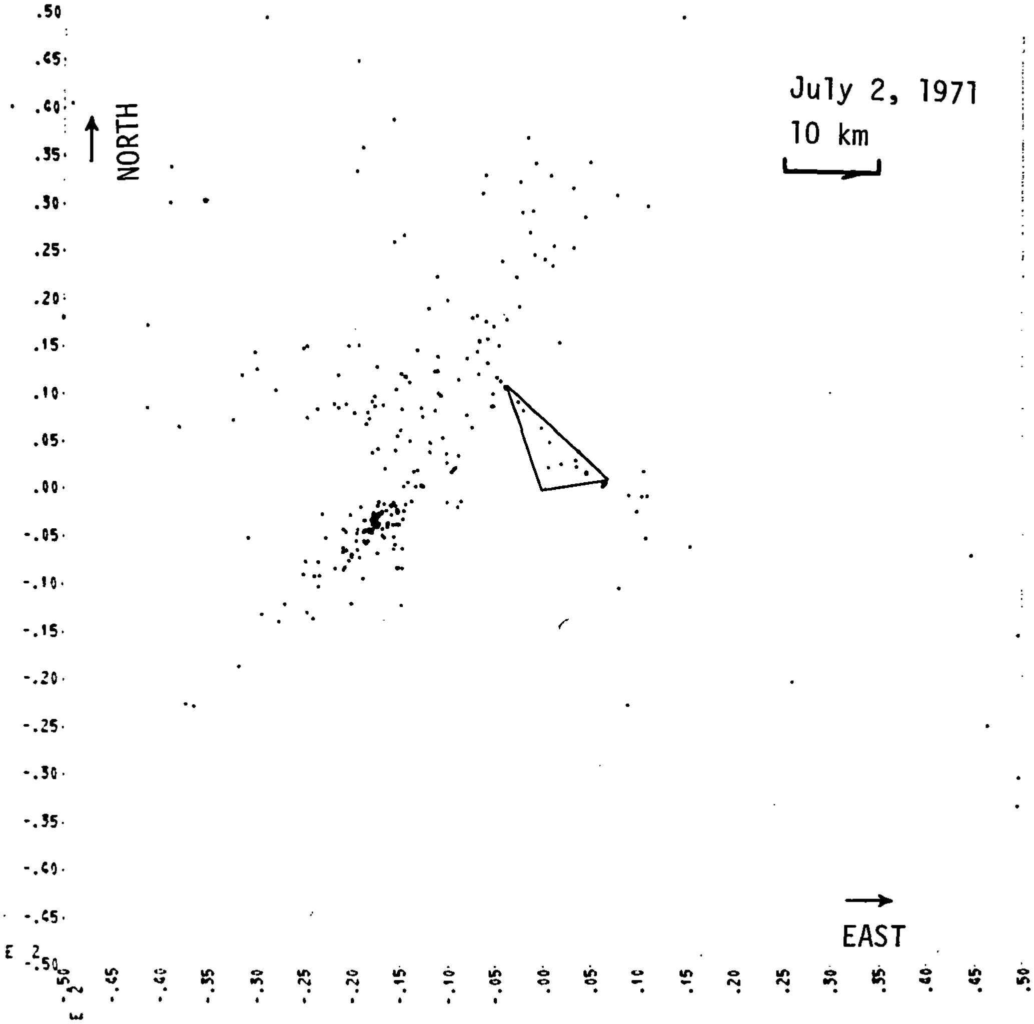

Figure 6. Lightning positions from uncorrected directional data from stations 2 and 3.

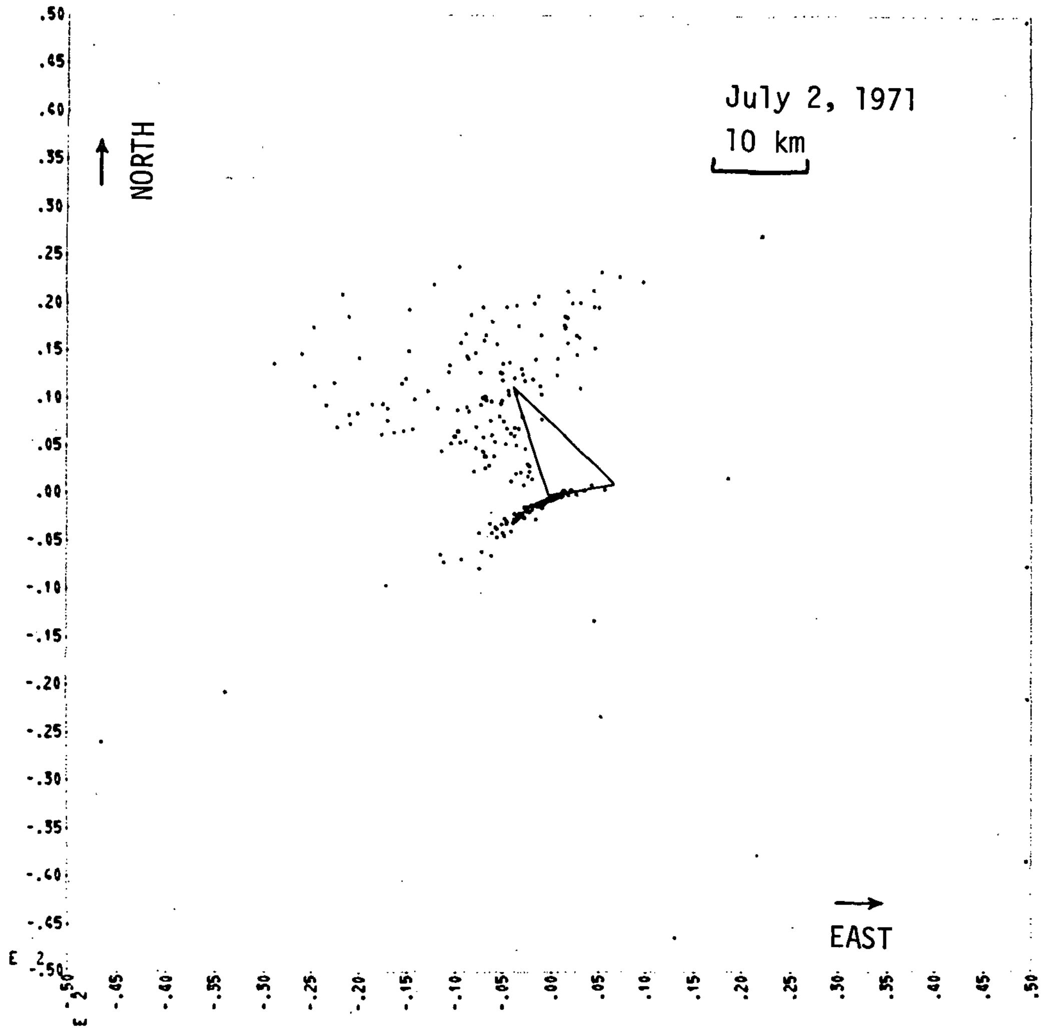

Figure 7. Lightning positions from uncorrected directional data from stations 1 and 3.

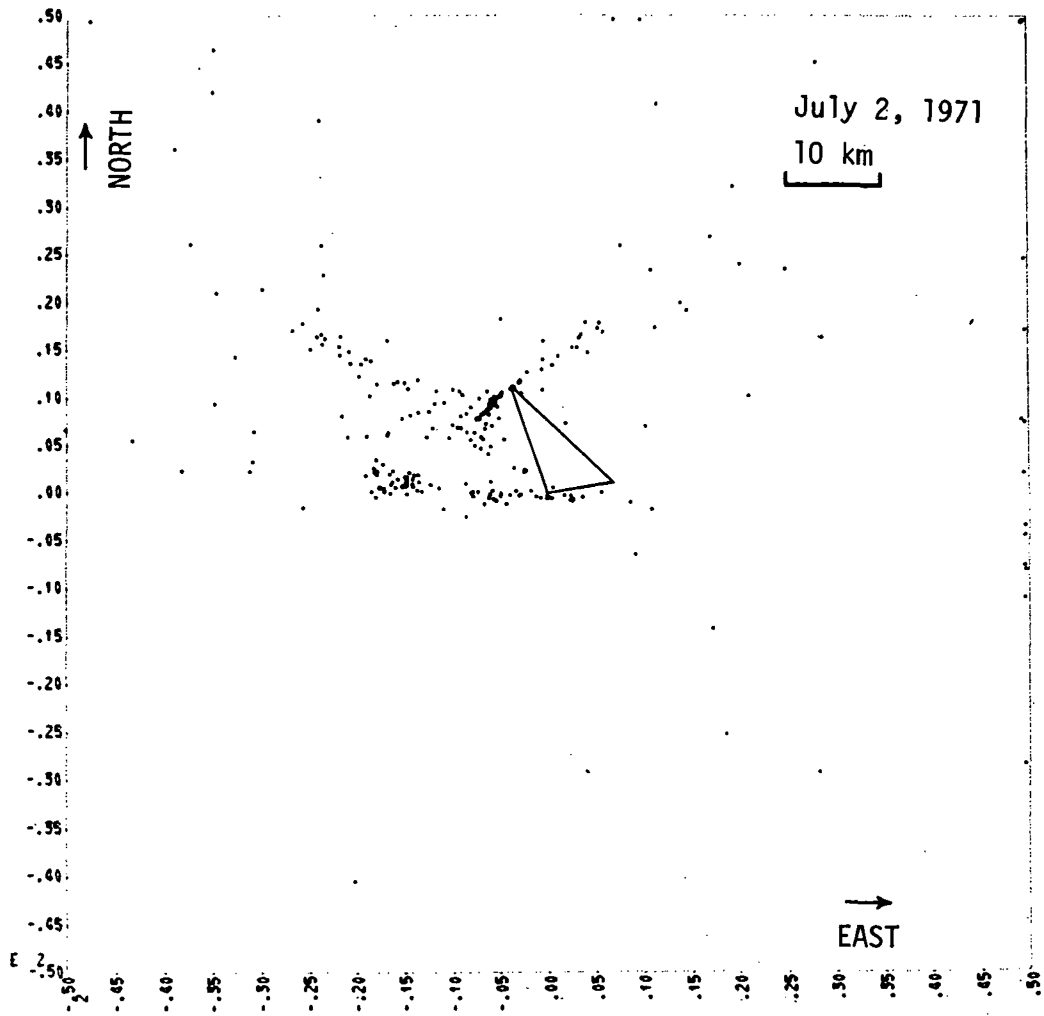

Figure 8. Lightning positions from operational VLF direction finders at stations 1 and 2.

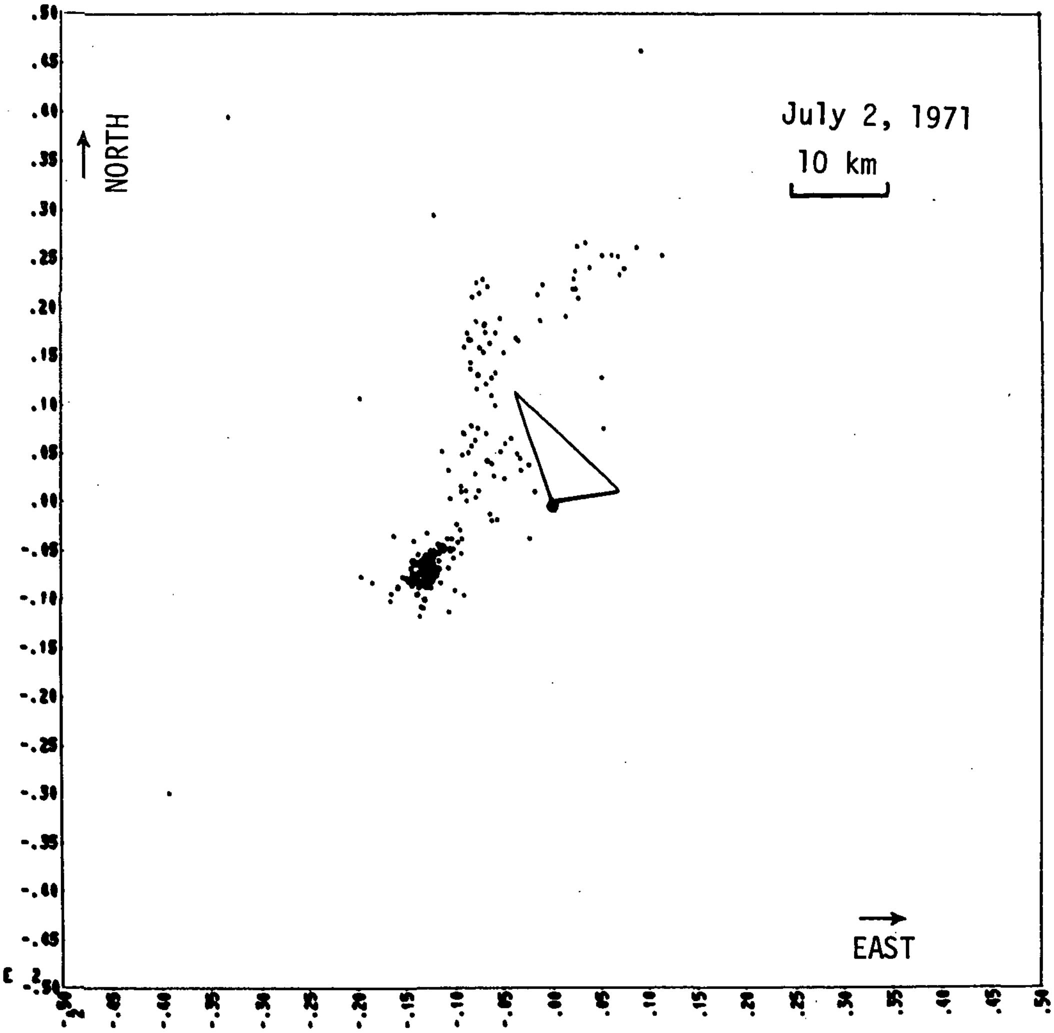

Figure 9. Lightning positions from uncorrected data of H and E at station 1.

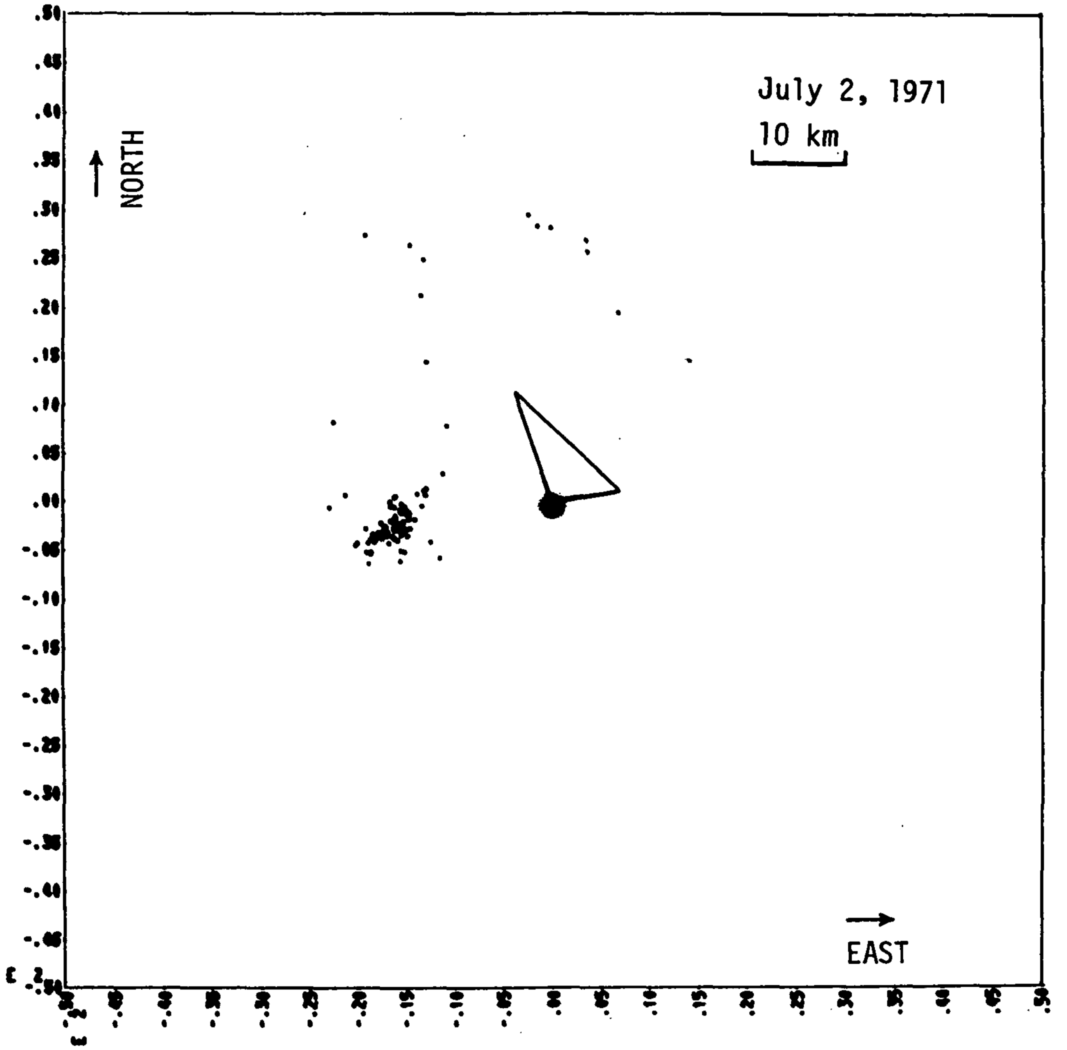

Figure 10. Lightning positions from uncorrected data of H and E at station 2.

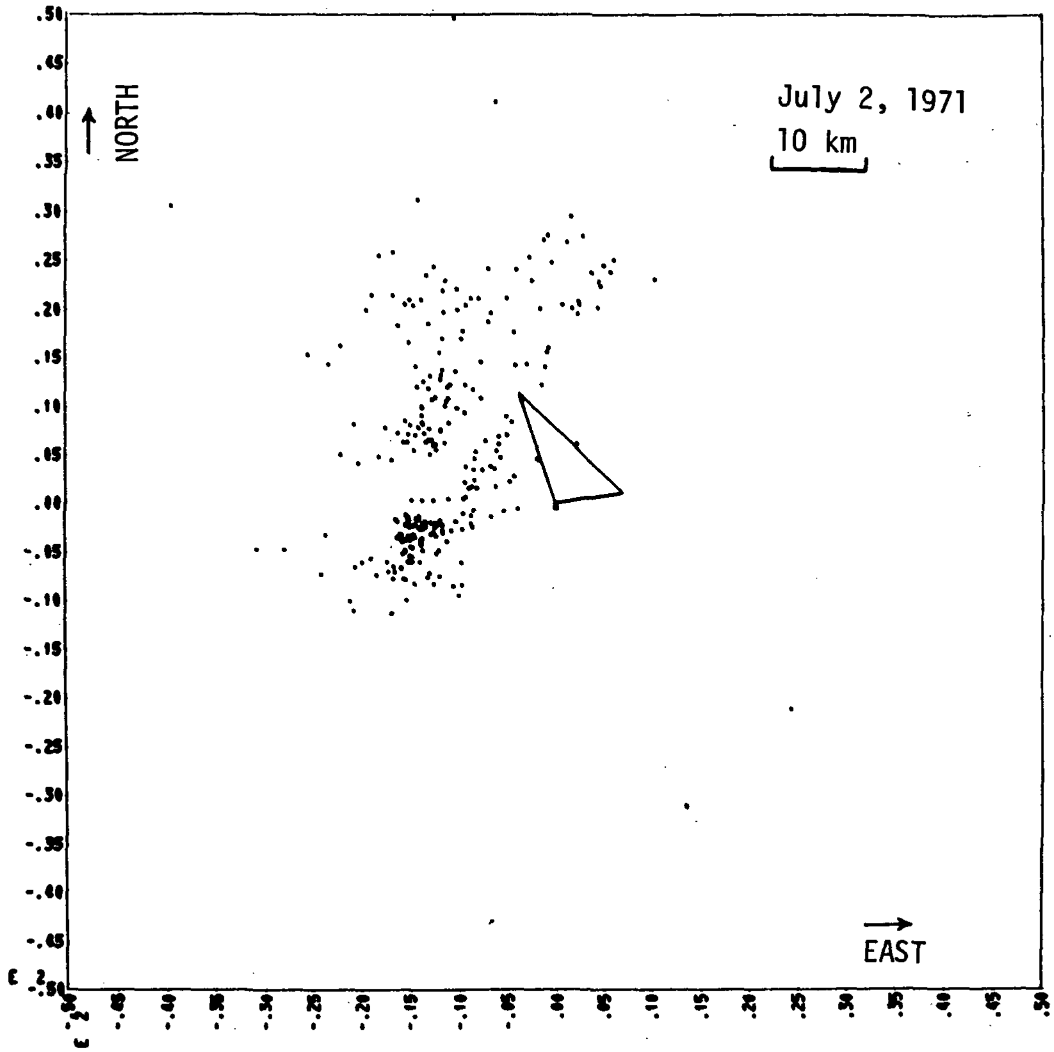

Figure 11. Lightning positions from uncorrected data of H and E at station 3.

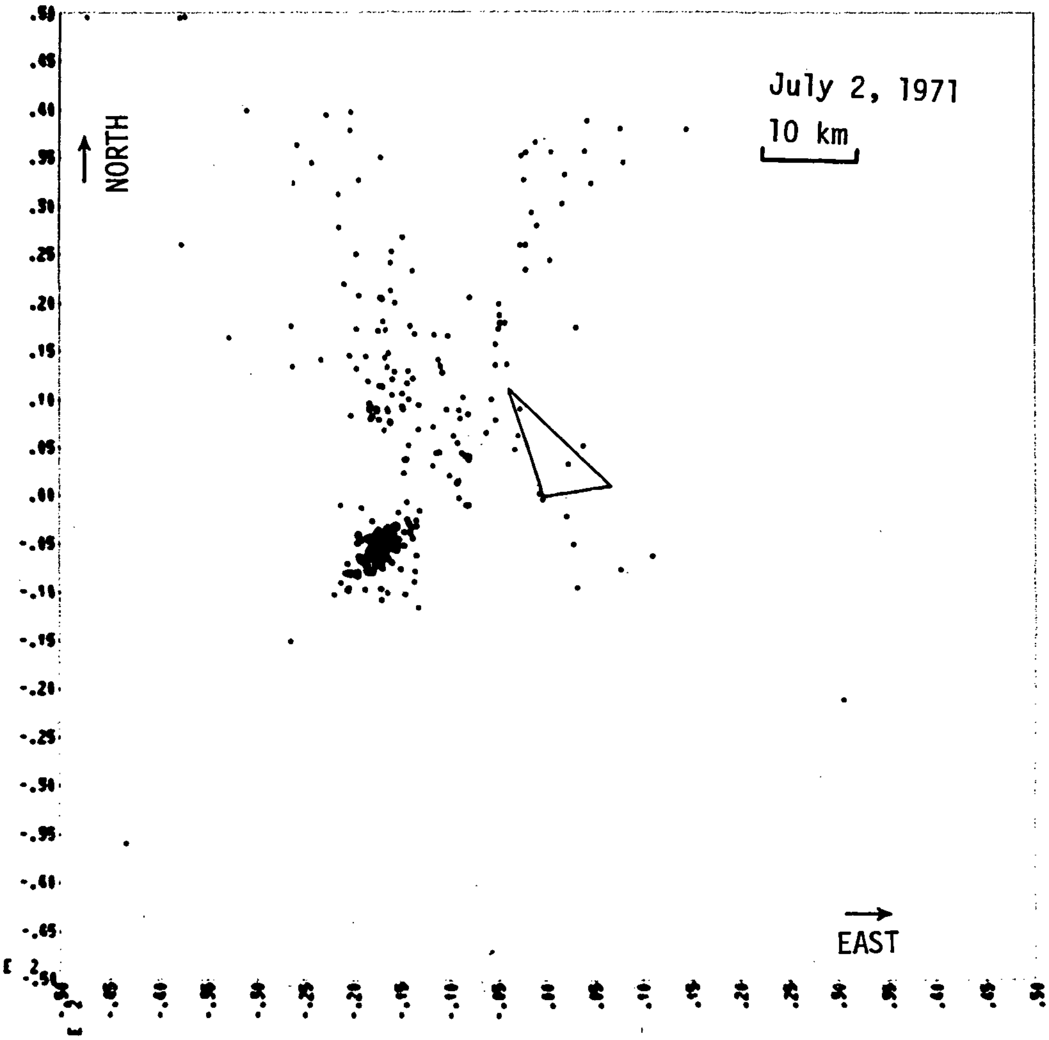

Figure 12. Lightning positions from corrected directional data from stations 1 and 2.

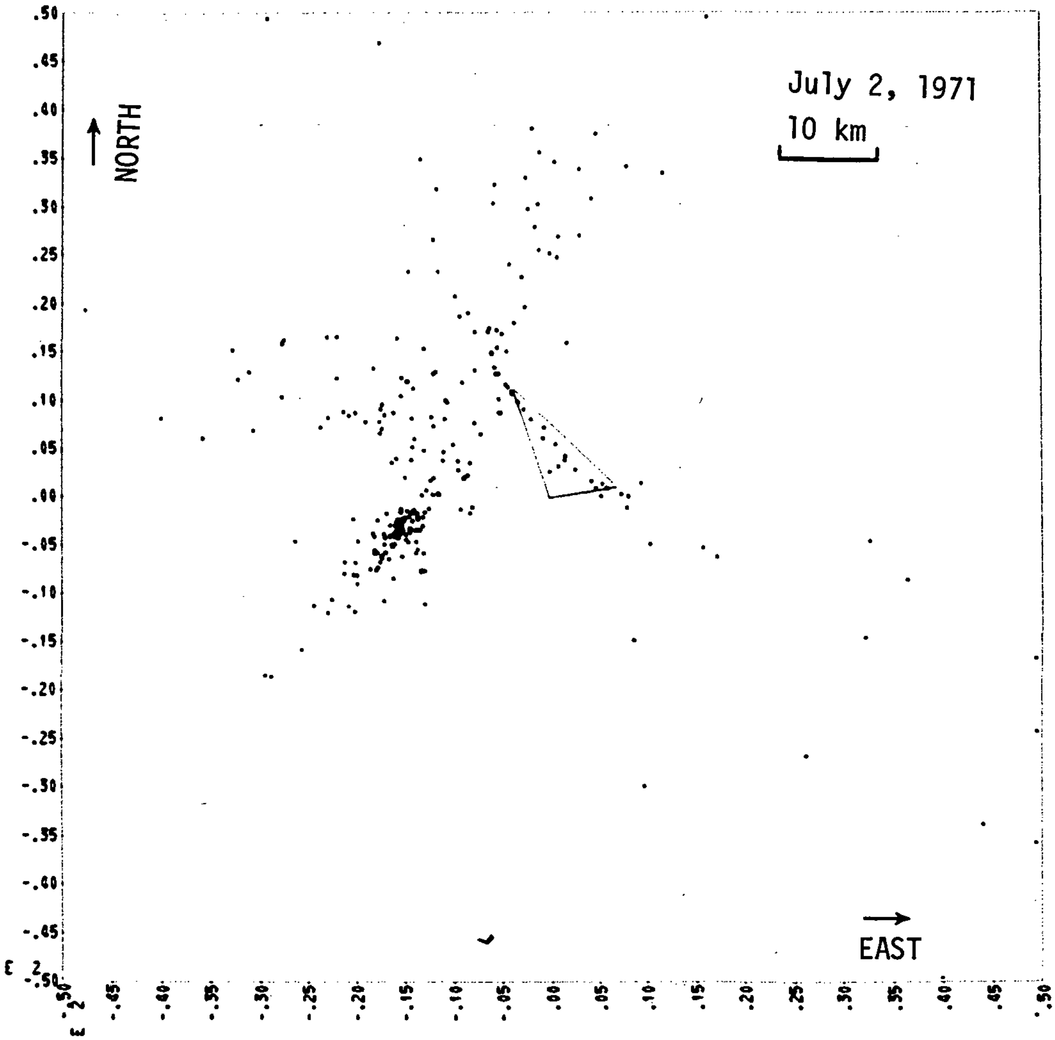

Figure 13. Lightning positions from corrected directional data from stations 2 and 3.

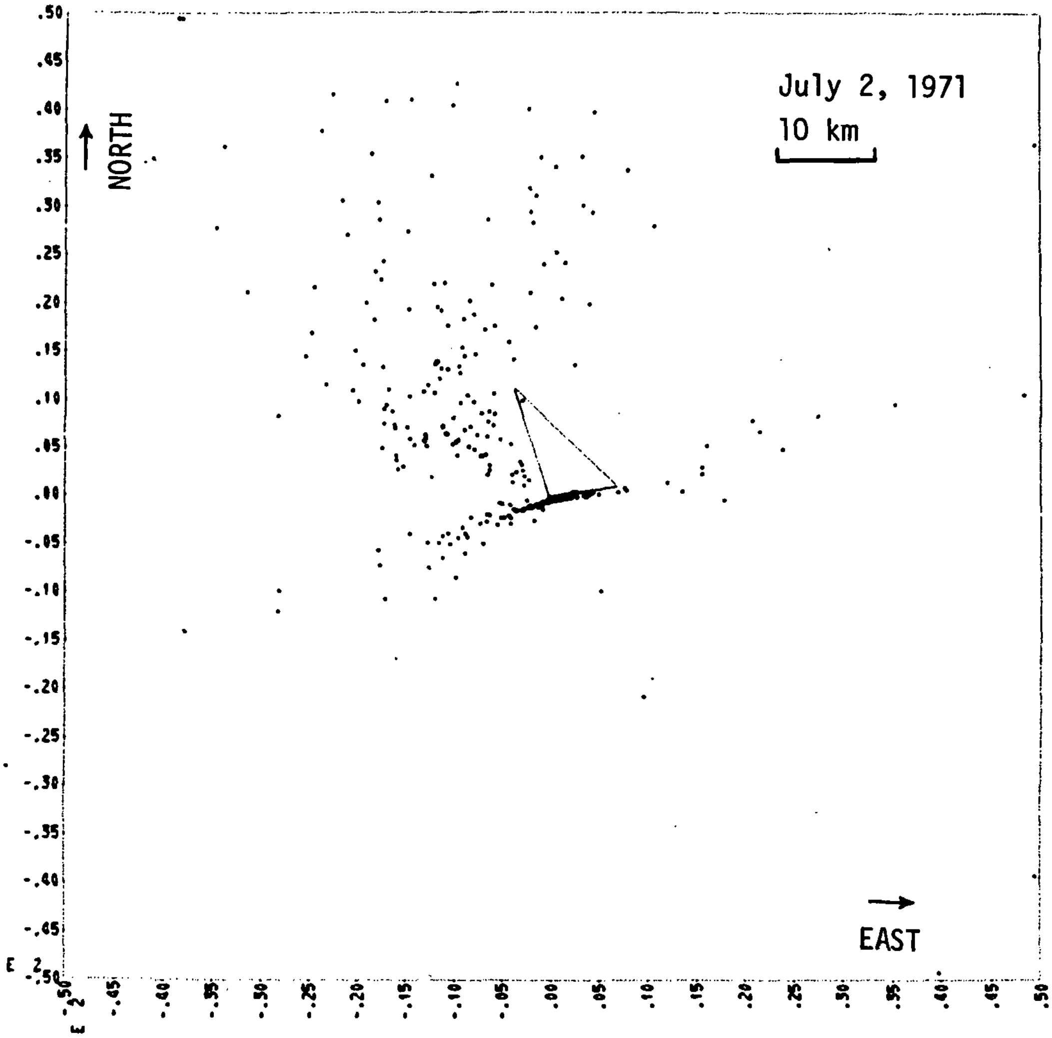

Figure 14. Lightning positions from corrected directional data from stations 1 and 3.

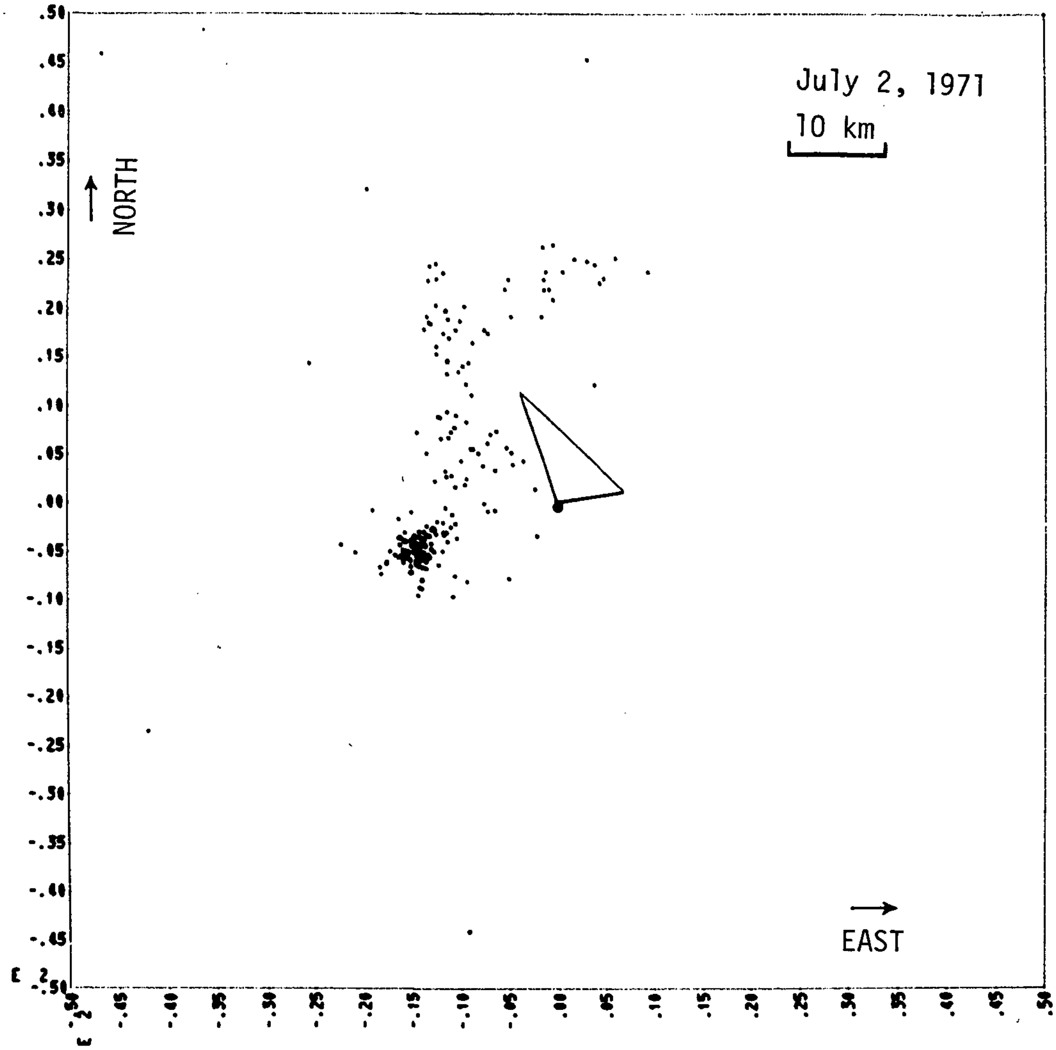

Figure 15. Lightning positions from corrected data of H and E at station 1.

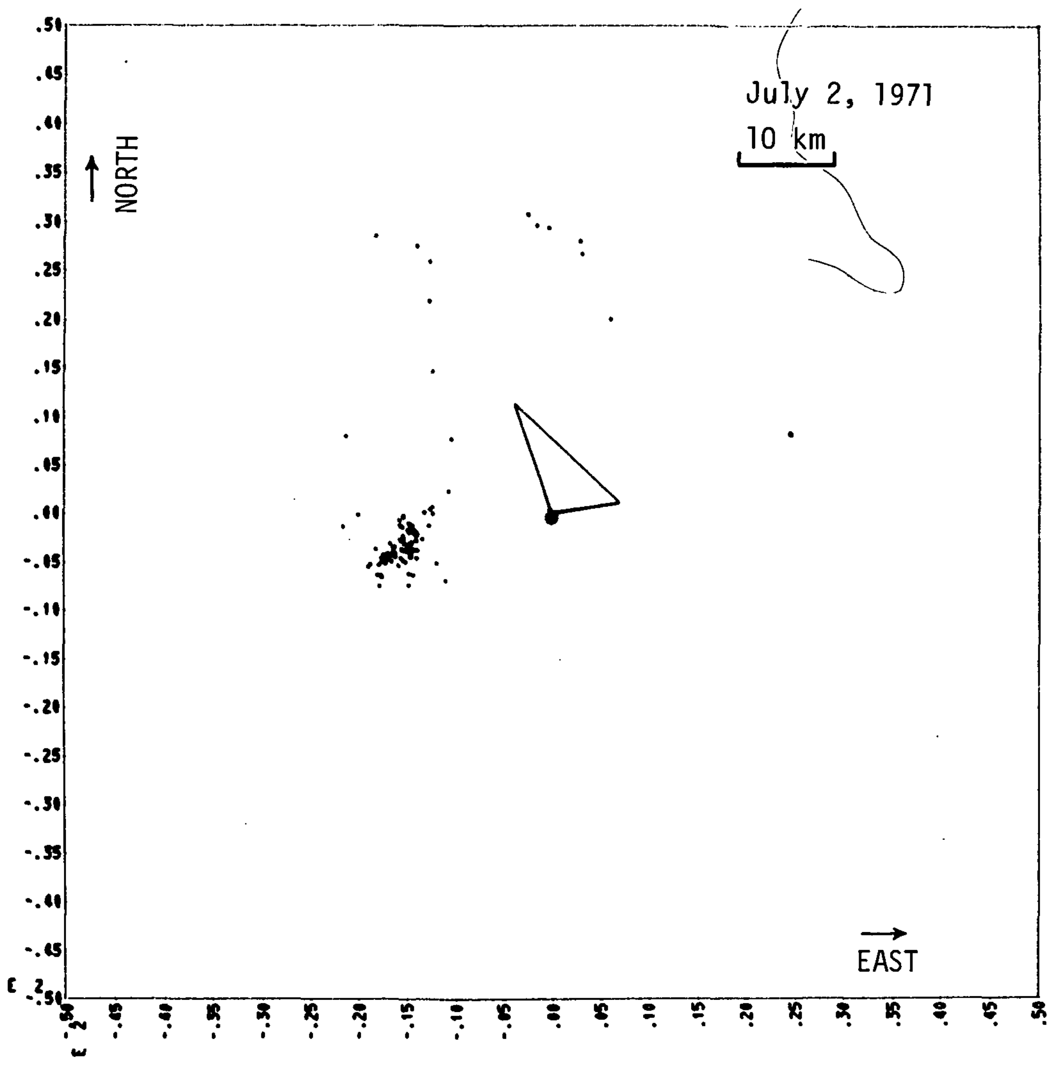

Figure 16. Lightning positions from corrected data of H and E at station 2.

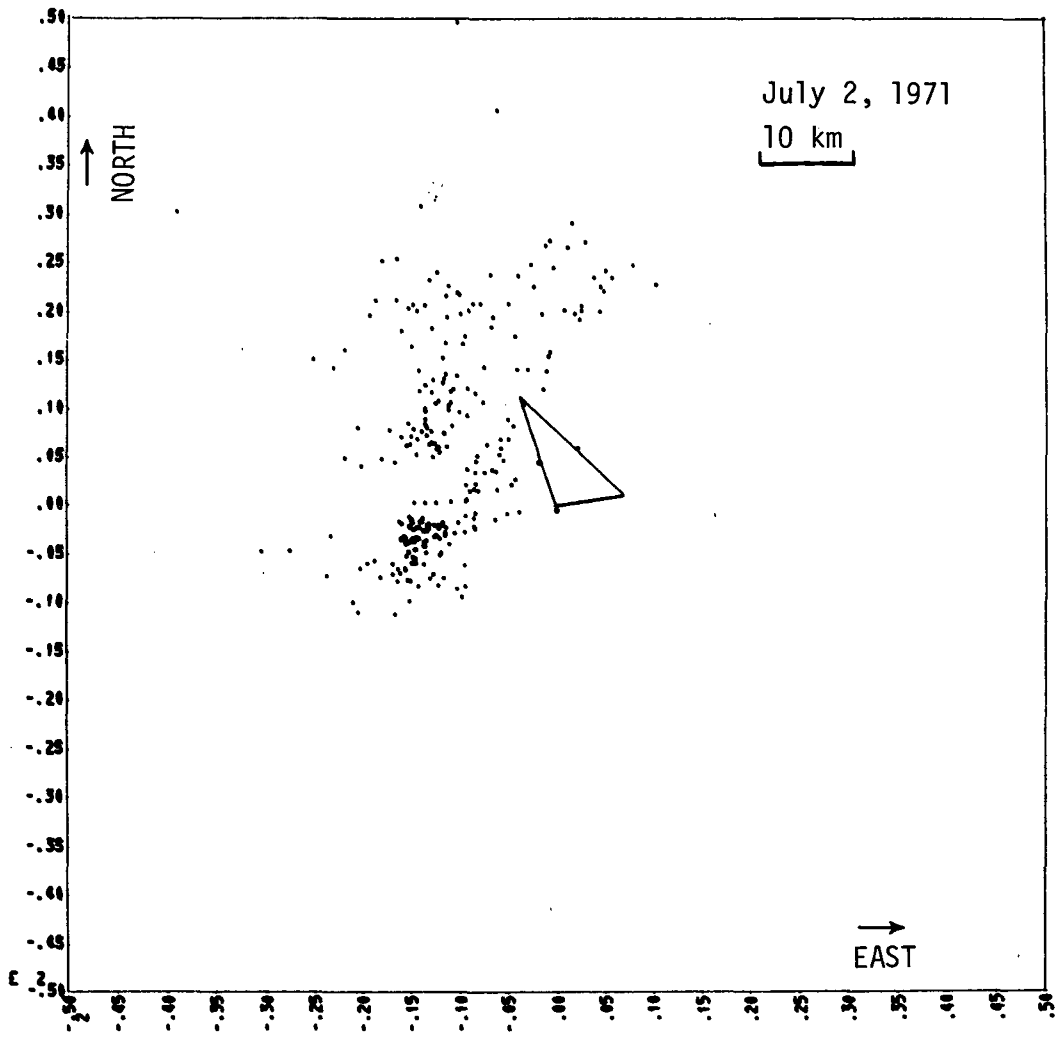

Figure 17. Lightning positions from corrected data of H and E at station 3.

lightning positions. The first storm seems centered over station 2 while the second storm seems centered over station 1. Most lightnings of this storm are close to baseline directions which results in a distortion such that the storm appears elongated along the baseline. These three figures show that the measurement system contains systematic errors, but before discussing data treatments, the other positioning data will be shown. In figure 8, lightning positions are plotted from the present operational lightning locating system. The direction finders were located at stations 1 and 2. The center of the first storm is 5 km southwest of station 2, but a wide scatter is apparent. The second storm stretches from station 1 for 15 km on westward. Thirty percent of the data appear either at unlikely locations (remember that during the observation period blue sky prevailed east of station 3), or unreasonably far away, as evidenced by the magnitude of the magnetic and electric field. Nevertheless, this plot represents fairly well the centers of thunderstorm activities.

In figure 9, lightning positions are plotted from data collected by station 1 only. Directions were derived from the ratio of the magnetic components as before, but the distance was calculated from the ratio of the magnetic field to electrostatic field. The inherent 180° ambiguity in the directional information was eliminated by determining the proper quadrant from directional data at site 2. The first storm appears centered over station 2, while the second storm seems to be clustered about 14 km southwest of station 1. The data scatters much less than the triangulation data, and no unreasonably far lightning is indicated. A similar plot is obtained from direction and distance data at station 2 (fig. 10). Most of the lightning of the first storm saturated the electric field channel, indicating the closeness of the storm. The position of the second storm appears 15 km west of station 1 and agrees reasonably with directional and distance data from station 1. Figure 11 finally depicts positions when using distance and direction data from station 3. In this plot a somewhat larger scatter is evident due to the 60 Hz noise pickup at this station. The first storm is centered again near station 2 and the second storm is indicated 15 km southwest of station 1.

From the data in figures 5 to 11 it is evident that lightning positions from single-station data are more consistent with each other than triangulation data. But before a final judgment can be made, it is appropriate that consistent errors be removed from the data and that an average error number also be derived for each data system.

By using directional data, we can plot a triangle with area F. The average area $\overline{F}$ over all lightning data was 36.4 km^2. Part of this value is due to random errors and cannot be eliminated, but part of it can be due to consistent errors such as antenna misalignment or secondary radiators. In a first test, (14) was applied to see if all three stations had properly aligned antennas. By calculating $\overline{F}$ as a function of β at all three stations, we found that misalignment errors were less than 1°. Next the constants A, B, and C of (17) were determined by using a computer search program to find the lowest average area $\overline{F}$. We found that station 1 had the largest distortion, probably because the antennas were mounted on top of a large steel-frame building. For this station the distortion parameters were A = 1.11, B = 0.19, and C = 1.31, which is equivalent to an increase of 40 percent of the magnetic field component at an azimuthal angle of 30° from true north. At station 2 only a 15 percent error in gain of the north-south component could be detected. This could be caused by poor adjustment of recorder amplifiers, or differences in the gain of the loop antenna circuits. The distortion components at station 2 were A = 1, B = 0, and C = 0.87. At station 3 no distortion could be detected.

After applying distortion corrections, the average area $\overline{F}$ over all lightning was 18.2 km^2, which is a considerable improvement. From this area we can estimate that the positioning error is about 6 km. This positioning error is equivalent to approximately 3° directional error at each station. When we consider that data leading to this estimate came from one storm that was overhead of one of the stations and a second storm that was only 15 km away, the experimentally found directional errors were expected.

Positioning data from ratios of the magnetic and electric field can also be used to calculate the average error area $\overline{F}$. The value using uncorrected magnetic field data is 9.5 km^2. Applying distortion correction changed this number to 4.8 km^2. This also is a significant improvement. The positioning error is about 3 km for this system. Figures 12 to 17 show again the same lightning positions as in figures 5 to 11 but with distortion correction applied. It is evident that improvements have been made and that data from single stations are inherently more consistent with each other than directional data from two-station networks.

The third system that gives positioning data is based on the assumption that the electrostatic field of a lightning decreases with the third power of the distance. Again an average area $\overline{F}$ can be calculated assuming a constant dipole moment for all lightning. The area $\overline{F}$ so obtained was 13.9 km^2. That is larger than the error area obtained from data on the ratio of magnetic-to-electric fields but smaller than the error area obtained from triangulation data.

5. CONCLUSIONS

It has been demonstrated that lightning position can be sensed by automatic equipment. A three-station network senses at 400 Hz the north and east component of the magnetic field and the electrostatic field. This three-station arrangement that uses three methods of evaluation gives redundant data on lightning positions.

The first method uses only directional data from which triangulation lightning positions are derived. This method proved the least accurate when compared with the other two methods. Apparently random errors caused by horizontal component of lightning signals combined with finite ground conductivities limit the accuracy of this method, so that on the average the indicated lightning position is within 6 km of the real lightning.

The second method uses directional and distance data from one station. Distance is determined from the ratio of the magnetic to electric field. This method is less affected by distortions produced by inhomogeneities in the ground and by secondary radiators and also less affected by random error sources. The accuracy of determining lightning position is on the average 3 km.

The third method uses distance information derived from the magnitude of the electrostatic field produced by lightning. Because the electrostatic field decreases with the third power of the distance, distance to a stroke can be estimated well from the field amplitude if the electric dipole moment of lightnings have only a modest variation. The data indicate that lightning position can be determined within 5 km on the average with this method. This agrees well with earlier observations of determining distance to lightning strokes from electrostatic field strength measurements (Ruhnke, 1962).

5. ACKNOWLEDGMENTS

This work was cosponsored by the National Aeronautics and Space Administration under contract number NASA-CC-59753.

6. REFERENCES

Ruhnke, L.H. (1971), Determining distances to lightning strokes from a single station. NOAA Tech. Rept. ERL 195-APCL 16 (Supt. of Documents, U.S. Government Printing Office, Washington, D.C.).

Ruhnke, L.H. (1962), Distance to lightning strokes as determined from electrostatic field strength measurements, J. Appl. Meteorol. **1**, No. 4, 544-547.

APPENDIX

Lightning Data at Kennedy Space Center During July 1971

(Raw Data)

	HX1	HXY1	HY1	E1	HX2	HXY2	HY2	E2	HX3	HXY3	HY3	E3	X1	X2	Y1	Y2	NO
71: 7: 2:15:34: 5	38	500	70	420	120	500	103	500	52	140	25	100	18	-284	-31	-237	1
71: 7: 2:15:34:14	25	220	45	298	75	500	60	500	26	52	25	70	25	-22	-34	-48	2
71: 7: 2:15:34:36	200	500	78	500	210	0	160	500	78	148	20	332	135	11	-89	-3	3
71: 7: 2:15:34:60	20	285	112	500	88	500	270	500	40	213	50	210	10	-121	-25	-56	4
71: 7: 2:15:35: 6	39	486	79	450	110	500	112	500	40	175	40	112	16	-174	-29	-97	5
71: 7: 2:15:35:21	12	52	140	500	15	0	410	500	42	500	70	300	2	-428	-66	2	6
71: 7: 2:15:35:55	7	25	98	500	28	200	30	254	29	122	41	200	-1	-234	-11	-162	7
71: 7: 2:15:36:15	15	72	34	210	54	500	52	500	28	33	15	50	6	8	8	-18	8
71: 7: 2:15:36:38	6	30	75	500	30	500	200	500	28	75	28	155	-6	-217	-7	-214	9
71: 7: 2:15:36:50	36	500	99	500	125	500	166	500	40	200	42	140	6	-95	-4	-23	10
71: 7: 2:15:37: 0	28	500	60	445	94	500	96	500	30	75	25	92	28	-469	-41	-435	11
71: 7: 2:15:37:23	34	450	54	435	109	500	103	500	20	72	31	102	17	-61	-26	-58	12
71: 7: 2:15:37:36	27	273	48	350	81	500	76	500	30	52	20	87	14	-206	-23	-195	13
71: 7: 2:15:37:45	30	500	82	428	115	500	129	500	39	155	37	103	13	14	-24	1	14
71: 7: 2:15:38:21	30	384	63	359	84	500	99	500	35	102	28	88	83	-456	-128	-125	15
71: 7: 2:15:38:37	27	252	46	319	82	500	70	500	25	52	20	55	19	-107	19	-102	16
71: 7: 2:15:38:59	24	500	60	196	65	500	70	370	40	139	27	50	-2	-89	9	-69	17
71: 7: 2:15:39:36	18	122	48	280	50	500	72	405	20	55	30	55	5	-96	-10	-46	18
71: 7: 2:15:39:45	19	138	42	252	100	500	69	500	29	60	20	79	27	-107	27	-102	19
71: 7: 2:15:39:54	43	500	82	500	115	500	124	500	41	170	37	128	33	-713	-53	-656	20
71: 7: 2:15:40: 3	12	102	40	168	26	0	11	326	20	37	18	45	11	-61	-1	-19	21
71: 7: 2:15:40:14	34	500	92	418	94	500	80	500	39	215	48	116	18	-254	-40	-194	22
71: 7: 2:15:40:34	28	327	58	319	85	500	87	500	33	85	36	81	-2	-43	-1	1	23
71: 7: 2:15:40:44	9	98	58	500	91	500	210	500	19	75	37	140	9	-319	-31	-309	24
71: 7: 2:15:41:14	25	500	78	428	92	500	134	500	33	150	42	112	26	-608	-34	-547	25
71: 7: 2:15:41:24	20	225	53	290	68	500	84	500	29	68	27	75	27	-73	27	-74	26
71: 7: 2:15:41:30	76	500	60	500	145	0	105	500	37	75	20	167	55	-102	-51	-133	27
71: 7: 2:15:42: 3	22	272	53	380	74	500	110	500	28	60	35	100	3	-345	-14	-305	28
71: 7: 2:15:43: 0	15	150	48	297	47	500	79	500	18	47	26	70	10	-119	-23	-70	29
71: 7: 2:15:43:22	15	263	88	500	65	500	145	500	29	151	50	140	16	-340	-29	-313	30
71: 7: 2:15:44:15	50	500	180	500	204	500	328	500	73	500	89	231	7	-760	-30	242	31
71: 7: 2:15:44:29	16	175	48	215	55	500	71	500	21	56	25	60	11	-52	-21	-72	32
71: 7: 2:15:44:47	14	115	35	180	39	500	58	362	16	20	20	50	8	-74	-15	-68	33
71: 7: 2:15:45:12	66	500	40	500	79	0	119	500	30	10	10	120	37	-81	-29	6	34
71: 7: 2:15:45:39	29	500	143	500	108	500	242	500	54	500	68	181	29	-900	-91	-250	35
71: 7: 2:15:46: 4	55	500	100	500	150	500	150	500	52	235	39	138	42	-115	-62	543	36
71: 7: 2:15:46:13	90	500	68	500	201	0	4	500	57	170	27	160	-9	-180	-29	-126	37
71: 7: 2:15:46:34	76	500	70	500	210	450	22	500	52	172	29	142	75	-33	-73	-56	38
71: 7: 2:15:47: 0	15	238	131	500	80	500	320	500	41	500	57	240	5	-477	-37	-453	39
71: 7: 2:15:47:14	24	323	65	342	70	500	108	500	28	65	30	88	20	-200	-36	-160	40
71: 7: 2:15:47:23	109	500	84	500	270	240	12	500	79	161	25	188	-41	-323	33	-434	41
71: 7: 2:15:48:39	69	500	95	500	200	500	116	500	55	500	49	135	48	-837	-61	-76	42
71: 7: 2:15:48:50	100	500	115	500	440	0	111	500	65	199	28	265	106	148	-99	-18	43
71: 7: 2:15:50:14	20	500	76	384	72	500	138	500	30	111	35	102	28	-363	-65	-287	44
71: 7: 2:15:50:25	5	100	86	441	20	409	182	500	30	130	40	126	4	-48	5	-49	45
71: 7: 2:15:51:29	37	500	100	500	114	500	166	500	49	500	49	113	29	-91	-34	1	46
71: 7: 2:15:51:59	15	238	70	398	55	500	130	500	22	95	38	92	23	-768	-32	-738	47
71: 7: 2:15:53:15	41	500	138	500	140	500	218	500	62	500	61	215	9	-491	-41	-387	48
71: 7: 2:15:53:40	8	0	82	301	12	0	116	500	15	70	49	106	-3	-55	-14	-34	49
71: 7: 2:15:53:49	5	105	110	500	19	348	209	500	25	190	64	150	1	-87	-65	-127	50
71: 7: 2:15:54: 2	10	100	50	288	42	500	110	500	19	52	26	70	6	-158	-21	-107	51
71: 7: 2:15:54:54	10	0	50	105	22	0	70	500	6	19	23	20	3	-6	6	-19	52
71: 7: 2:15:56:34	4	0	43	180	5	0	65	306	8	25	29	60	-2	-13	-7	-25	53

71: 7: 2:15:56:49	20	48	60	255	10	56	100	500	20	44	29	85	-1	-193	-20	-111	54
71: 7: 2:15:57: 0	30	235	32	389	106	500	26	500	24	41	10	74	17	21	-19	-16	55
71: 7: 2:15:57:25	6	0	65	285	10	0	110	500	12	54	40	94	-10	-352	-47	-262	56
71: 7: 2:15:57:42	5	0	59	295	19	0	100	500	12	41	26	93	-5	-357	-22	-271	57
71: 7: 2:15:58:28	15	0	50	205	41	0	33	335	9	12	29	40	15	13	-15	-16	58
71: 7: 2:15:59: 0	21	176	30	360	91	500	32	500	10	30	19	72	17	23	-19	-22	59
71: 7: 2:15:59:36	0	0	72	315	10	0	111	500	10	56	30	111	-4	-49	-17	-43	60
71: 7: 2:15:59:45	30	500	60	500	150	500	90	500	39	95	24	110	10	-42	-27	-50	61
71: 7: 2:15:59:57	4	20	100	464	4	22	106	500	26	152	56	138	1	-206	-82	-256	62
71: 7: 2:16: 0: 0	5	35	80	360	14	222	130	500	20	114	48	124	1	-190	-30	-123	63
71: 7: 2:16: 0:31	42	500	54	500	140	500	59	500	32	82	24	100	37	-90	-44	-80	64
71: 7: 2:16: 0:46	65	450	30	500	130	0	20	500	40	23	12	100	30	19	-21	-4	65
71: 7: 2:16: 0:50	220	500	109	500	420	0	93	500	120	400	45	339	99	76	-82	-32	66
71: 7: 2:16: 0:55	11	0	85	308	32	0	145	500	14	80	45	130	-6	-75	-17	-46	67
71: 7: 2:16: 2: 1	6	0	37	140	12	0	56	284	5	0	28	54	-6	-211	-21	-102	68
71: 7: 2:16: 2:13	16	0	240	500	42	0	400	500	53	445	121	360	-19	187	-149	773	69
71: 7: 2:16: 2:22	19	155	35	300	90	500	37	500	20	16	10	50	14	24	-17	-24	70
71: 7: 2:16: 2:36	70	500	95	500	240	500	110	500	55	260	42	184	6	-107	7	-102	71
71: 7: 2:16: 2:58	78	500	110	500	267	500	151	500	62	228	40	199	90	31	-109	-180	72
71: 7: 2:16: 3:12	120	500	137	500	308	500	110	500	90	432	51	260	-59	-719	49	572	73
71: 7: 2:16: 3:59	136	500	66	500	313	383	53	500	81	215	29	223	45	13	-45	-14	74
71: 7: 2:16: 4: 0	100	500	59	500	203	0	25	500	60	130	19	180	118	110	-93	-35	75
71: 7: 2:16: 4:33	31	442	60	500	89	500	94	500	34	79	20	108	34	-7	-48	-71	76
71: 7: 2:16: 4:48	60	500	85	500	219	500	108	500	51	175	30	164	52	-916	-63	-900	77
71: 7: 2:16: 5:22	50	500	84	500	195	500	128	500	42	158	31	169	47	-175	-60	-266	78
71: 7: 2:16: 5:42	74	500	75	500	240	500	39	500	56	190	30	166	58	-25	-57	-49	79
71: 7: 2:16: 6:17	30	328	55	397	100	500	70	500	29	52	20	85	17	-322	-34	-211	80
71: 7: 2:16: 6:55	84	500	58	500	174	0	25	500	54	116	20	143	105	-16	-80	-26	81
71: 7: 2:16: 7: 9	20	0	100	379	48	0	138	500	11	68	50	142	-30	-747	-64	-627	82
71: 7: 2:16: 8:20	58	385	29	500	112	0	12	500	29	44	12	111	40	34	-28	-6	83
71: 7: 2:16: 8:51	32	180	27	352	75	0	1	500	21	25	10	60	32	15	-20	-5	84
71: 7: 2:16: 9: 1	23	0	134	500	86	0	220	500	19	155	77	236	-28	109	-72	310	85
71: 7: 2:16: 9:10	21	49	12	105	35	0	5	165	51	105	20	148	55	50	-39	-14	86
71: 7: 2:16: 9:49	53	500	39	500	150	500	40	500	38	94	22	76	40	6	-31	-7	87
71: 7: 2:16:12:41	157	500	86	500	234	0	25	500	93	283	34	240	186	153	-133	-70	88
71: 7: 2:16:13:25	50	422	38	500	110	124	15	500	34	34	15	105	28	22	-20	-7	89
71: 7: 2:16:13:44	20	150	38	295	70	500	53	500	22	20	10	46	7	-7	-12	-20	90
71: 7: 2:16:14:27	112	500	61	500	228	0	17	500	68	194	27	190	103	-146	-81	-91	91
71: 7: 2:16:14:39	45	500	79	500	210	500	115	500	45	160	30	138	10	19	-13	-30	92
71: 7: 2:16:14:50	32	0	133	500	60	0	172	500	9	68	80	208	-54	-889	-89	-803	93
71: 7: 2:16:15:15	0	0	63	220	12	0	88	440	9	40	41	89	-12	-298	-39	-221	94
71: 7: 2:16:15:32	68	500	56	500	140	500	30	500	40	84	20	112	58	50	-42	-14	95
71: 7: 2:16:16:31	55	380	20	480	115	132	12	500	30	57	18	90	35	-21	-28	-15	96
71: 7: 2:16:16:41	20	67	69	300	59	500	102	500	5	18	38	110	3	12	-5	-17	97
71: 7: 2:16:17: 6	29	0	130	500	70	30	170	500	8	69	79	210	3	396	16	262	98
71: 7: 2:16:17:24	64	0	12	390	54	0	32	275	40	0	10	67	86	38	-27	11	99
71: 7: 2:16:17:44	71	454	28	500	120	0	15	500	45	22	10	96	77	-74	-48	-18	100
71: 7: 2:16:18: 0	42	500	70	500	180	500	118	500	37	129	28	139	35	-342	-41	-306	101
71: 7: 2:16:18:28	80	500	42	500	146	0	18	500	52	75	12	120	97	81	-71	-24	102
71: 7: 2:16:18:50	42	0	125	460	90	0	152	500	3	0	79	187	-37	-273	-53	-138	103
71: 7: 2:16:19:55	48	500	48	500	154	500	29	500	33	90	25	118	35	36	-33	-26	104
71: 7: 2:16:20:12	32	200	27	345	82	0	5	500	25	14	9	61	27	23	-20	-6	105
71: 7: 2:16:20:32	65	455	30	500	129	0	24	500	38	59	14	112	58	45	-40	-11	106
71: 7: 2:16:20:41	50	231	22	500	52	234	50	500	23	6	10	60	17	-13	-23	15	107
71: 7: 2:16:21: 6	14	0	45	181	30	0	60	354	3	5	23	54	-5	-16	-8	-17	108
71: 7: 2:16:21:18	253	500	132	500	467	0	44	500	148	404	45	388	310	-105	-242	-332	109
71: 7: 2:16:21:32	35	500	62	500	406	0	43	500	30	50	18	145	25	8	-34	-39	110
71: 7: 2:16:22: 0	25	25	65	482	30	0	84	460	7	0	46	98	-20	-235	-31	-100	111
71: 7: 2:16:22:20	78	500	55	500	185	0	22	500	49	80	15	148	42	30	30	-8	112
71: 7: 2:16:22:41	76	500	57	500	192	103	8	500	46	124	25	146	79	47	-62	-10	113
71: 7: 2:16:23: 2	68	500	40	500	14	0	17	106	40	83	19	129	35	31	-23	-3	114
71: 7: 2:16:23:21	83	500	60	500	189	200	13	500	56	120	20	158	34	27	-25	-11	115
71: 7: 2:16:23:36	168	500	79	500	282	0	67	500	90	207	26	266	5	16	-20	-83	116
71: 7: 2:16:24:17	100	500	69	500	205	10	163	500	48	102	10	222	32	-2	-31	32	117

71:	7:	2:16:24:55	49	500	50	500	115	500	155	500	20	46	15	103	-7	-26	7	16	118
71:	7:	2:16:26:17	175	500	60	500	203	0	78	500	98	206	26	250	45	41	-35	-9	119
71:	7:	2:16:26:50	87	500	38	500	150	0	25	500	52	60	17	131	66	40	-42	-10	120
71:	7:	2:16:27: 5	35	0	70	296	70	0	80	500	0	0	54	130	-40	-176	-30	-77	121
71:	7:	2:16:27:36	12	0	116	470	15	0	150	500	16	143	71	207	-3	-24	-10	-31	122
71:	7:	2:16:27:44	84	500	70	500	200	500	45	500	55	211	37	180	104	-170	-89	-177	123
71:	7:	2:16:29: 1	92	500	61	107	204	107	32	500	56	103	19	177	62	4	-47	-1	124
71:	7:	2:16:29:22	39	250	60	108	260	0	130	500	30	20	9	149	20	97	-25	45	125
71:	7:	2:16:29:49	24	0	89	34	57	0	120	500	5	46	62	150	-35	-182	-46	-81	126
71:	7:	2:16:30:36	30	0	124	47	57	0	151	500	4	42	74	105	-45	-541	-71	-411	127
71:	7:	2:16:30:50	210	500	73	194	323	0	150	500	104	194	25	305	200	-7	-123	9	128
71:	7:	2:16:33:39	80	500	69	100	197	0	25	500	48	142	27	163	45	51	-45	-21	129
71:	7:	2:16:34:11	141	500	82	150	305	0	110	500	78	241	30	241	170	-50	-133	-110	130
71:	7:	2:16:34:26	44	245	53	13	105	0	52	500	39	32	10	70	-13	36	16	1	131
71:	7:	2:16:35:32	68	500	76	99	240	243	30	500	48	135	27	170	33	28	-27	-2	132
71:	7:	2:16:35:45	84	0	27	80	36	0	40	345	30	18	10	107	61	12	-9	10	133
71:	7:	2:16:36:47	50	31	36	80	33	6	60	500	20	10	10	54	5	11	6	6	134
71:	7:	2:16:37:32	170	500	90	200	135	0	212	500	68	50	10	300	80	-256	-59	-68	135
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71:	7:	2:16:38:21	38	159	38	45	80	41	6	500	25	39	13	70	8	-267	-1	-74	137
71:	7:	2:16:39:22	50	309	54	94	277	333	100	500	31	46	10	158	30	0	-28	24	138
71:	7:	2:16:39:56	30	0	11	15	16	0	15	86	16	0	10	33	-24	-7	-1	-4	139
71:	7:	2:16:40:12	80	500	93	242	253	46	48	500	41	83	20	270	17	16	-16	3	140
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71:	7:	2:16:41:55	119	500	85	176	382	0	159	500	73	136	21	277	54	72	-46	13	143
71:	7:	2:16:42:21	107	0	38	114	48	0	50	452	43	0	9	152	46	1	11	3	144
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71:	7:	2:16:49:15	155	0	40	162	65	0	78	500	55	0	8	194	102	6	-31	32	146
71:	7:	2:16:49:29	23	112	44	100	86	500	168	500	16	38	20	194	2	-60	7	34	147
71:	7:	2:16:50:11	150	0	27	150	76	0	73	500	53	34	9	198	98	-15	-26	43	148
71:	7:	2:16:51:12	395	700	169	500	389	0	307	500	154	400	46	500	231	-151	-192	-119	149
71:	7:	2:16:51:38	120	0	50	113	47	0	56	433	48	0	8	155	95	-4	-10	40	150
71:	7:	2:16:52:13	238	0	85	208	83	0	98	500	85	0	14	286	85	-104	-12	7	151
71:	7:	2:16:52:52	173	0	84	146	56	0	76	500	65	0	18	208	85	-195	-12	-18	152
71:	7:	2:16:53:14	282	196	22	266	128	0	205	500	92	48	12	325	66	-50	-30	6	153
71:	7:	2:16:53:30	330	275	22	370	277	0	190	500	125	111	12	480	121	53	-62	31	154
71:	7:	2:16:53:41	130	0	59	98	59	0	65	415	58	0	10	153	130	-143	-14	-13	155
71:	7:	2:16:53:55	23	0	34	100	25	30	15	115	28	0	13	72	35	43	-3	-1	156
71:	7:	2:16:54:41	149	0	65	140	51	0	65	500	60	0	14	187	111	-20	-8	-5	157
71:	7:	2:16:55: 9	195	0	96	135	79	0	92	500	80	0	13	218	17	-171	-2	-12	158
71:	7:	2:16:55:44	140	0	54	96	68	0	64	431	64	0	10	159	-80	7	-8	33	159
71:	7:	2:16:56:51	118	0	48	97	60	0	55	500	56	0	13	150	-2	1	-16	5	160
71:	7:	2:16:57:25	99	94	12	125	60	0	99	500	35	10	9	132	60	-163	-35	-7	161
71:	7:	2:16:58:18	146	0	56	150	55	0	68	500	50	0	9	190	-12	-12	-18	33	162
71:	7:	2:16:58:35	85	0	41	66	39	0	40	275	40	0	15	102	74	19	-7	15	163
71:	7:	2:16:58:50	150	0	18	232	38	0	76	500	40	0	9	214	101	-221	-41	-34	164
71:	7:	2:16:59: 4	310	325	70	328	276	0	240	500	115	191	23	435	85	-104	-36	-36	165
71:	7:	2:16:59:31	73	0	37	55	34	0	37	405	35	0	10	88	54	13	-5	13	166
71:	7:	2:16:59:40	170	0	66	116	73	0	75	500	72	0	12	188	62	-154	-8	-6	167
71:	7:	2:16:59:59	440	455	70	465	355	0	460	500	159	213	24	500	103	-254	-65	-124	168
71:	7:	2:17: 0:20	150	0	50	125	56	0	69	478	60	0	11	177	100	-27	-19	10	169
71:	7:	2:17: 0:45	365	500	78	478	449	0	259	500	144	275	33	500	146	-78	-82	-20	170
71:	7:	2:17: 1: 2	108	0	59	83	48	0	55	350	50	0	10	130	152	16	-14	45	171
71:	7:	2:17: 1:15	105	0	44	89	50	0	51	355	48	0	10	136	80	23	-9	22	172
71:	7:	2:17: 1:31	196	0	46	312	40	0	105	500	54	0	10	257	86	-133	-34	-49	173
71:	7:	2:17: 1:54	140	0	65	102	56	0	67	425	58	0	10	160	58	-106	-7	7	174
71:	7:	2:17: 2: 1	195	0	72	171	80	0	86	500	80	0	18	241	171	-120	-24	-16	175
71:	7:	2:17: 2:29	70	0	35	50	31	0	34	245	33	0	10	98	81	32	-5	24	176
71:	7:	2:17: 2:39	107	0	42	81	42	0	55	335	46	0	12	122	44	-2	-10	29	177
71:	7:	2:17: 3:34	119	0	28	210	19	0	48	500	29	0	9	125	74	-71	-18	18	178
71:	7:	2:17: 4: 6	79	0	42	55	36	0	42	289	38	0	11	107	88	-3	-11	29	179
71:	7:	2:17: 4:36	100	0	48	80	48	0	48	362	41	0	10	128	81	1	-9	13	180
71:	7:	2:17: 4:46	420	500	80	466	424	0	247	500	174	276	29	500	205	-38	-140	2	181

71: 7: 2:17: 4:59	89	0	27	81	44	0	37	300	32	0	10	120	54	11	-10	9	182
71: 7: 2:17: 5: 0	112	500	84	172	174	0	163	500	59	59	9	216	100	-100	-74	20	183
71: 7: 2:17: 5:39	19	0	29	35	60	312	59	500	52	0	15	113	95	-29	-6	-1	184
71: 7: 2:17: 6:28	39	281	62	121	85	0	140	500	18	21	15	87	36	-209	-36	1	185
71: 7: 2:17: 6:37	105	0	38	90	50	0	50	380	43	0	10	130	88	23	-16	16	186
71: 7: 2:17: 6:59	88	0	40	70	40	0	41	308	40	0	10	113	89	10	-8	16	187
71: 7: 2:17: 7: 8	160	0	82	169	60	0	72	500	65	0	15	228	104	-41	-10	34	188
71: 7: 2:17: 7:44	75	0	32	73	35	0	35	307	30	8	8	107	53	10	-7	10	189
71: 7: 2:17: 8: 9	160	0	71	120	68	0	74	500	74	0	15	185	69	21	-5	50	190
71: 7: 2:17: 9: 6	97	0	40	76	48	0	48	330	43	0	10	123	68	16	-9	14	191
71: 7: 2:17: 9:15	62	0	32	42	33	0	31	180	30	0	12	74	73	18	-8	14	192
71: 7: 2:17: 9:41	68	0	36	42	29	0	30	185	20	0	9	78	66	13	-5	11	193
71: 7: 2:17:10:10	104	0	52	80	48	0	50	370	48	0	9	126	87	6	-7	-830	194
71: 7: 2:17:10:26	130	0	70	99	50	0	63	405	58	0	16	150	41	-178	-1	-5	195
71: 7: 2:17:11: 4	315	0	168	235	130	0	144	500	138	0	37	388	154	-136	-13	-10	196
71: 7: 2:17:11:38	72	0	40	61	32	0	36	245	32	0	8	95	64	-4	-3	10	197
71: 7: 2:17:12: 1	64	0	27	45	32	0	32	238	25	0	10	56	70	12	-10	11	198
71: 7: 2:17:12:18	93	0	35	75	50	0	42	354	45	0	9	118	70	33	-12	19	199
71: 7: 2:17:12:48	78	0	32	69	38	0	36	285	38	0	13	100	60	13	-9	11	200
71: 7: 2:17:13:18	102	0	66	78	50	0	54	349	52	0	18	132	88	3	-6	17	201
71: 7: 2:17:13:27	115	0	46	87	60	0	55	422	54	0	9	140	97	9	-18	19	202
71: 7: 2:17:13:46	113	0	59	70	55	0	55	326	55	0	19	126	118	24	-11	33	203
71: 7: 2:17:14: 1	232	0	100	186	95	0	106	500	99	0	22	278	113	-79	-23	22	204
71: 7: 2:17:14:18	145	0	70	100	66	0	72	440	66	0	15	175	95	1	12	33	205
71: 7: 2:17:14:58	54	0	28	36	28	0	29	172	24	0	10	45	66	14	-9	11	206
71: 7: 2:17:15: 7	120	0	49	90	64	0	57	441	60	0	13	150	86	39	-11	23	207
71: 7: 2:17:15:17	223	0	110	180	89	0	99	500	98	0	20	289	61	-146	-9	-2	208
71: 7: 2:17:17:22	83	0	49	68	36	0	40	292	41	0	14	110	80	22	-3	19	209
71: 7: 2:17:17:39	142	0	79	110	62	0	71	470	70	0	24	174	140	-47	-6	43	210
71: 7: 2:17:17:51	20	0	15	5	54	0	54	353	52	0	13	133	76	35	-12	21	211
71: 7: 2:17:19:44	133	0	64	100	61	0	65	439	60	0	10	164	62	9	-11	8	212
71: 7: 2:17:20: 0	267	0	110	186	110	0	120	500	113	0	22	303	87	-143	-20	-23	213
71: 7: 2:17:20:14	122	0	71	91	58	0	60	378	47	0	12	155	95	23	-60	18	214
71: 7: 2:17:20:38	130	0	64	90	62	0	64	394	59	0	14	153	75	27	-11	19	215
71: 7: 2:17:20:48	88	0	53	70	40	0	45	300	43	0	10	66	68	4	4	35	21(
71: 7: 2:17:21: 2	100	0	46	76	48	0	48	315	40	0	10	120	103	-4	-11	7	217
71: 7: 2:17:21:20	194	0	105	115	82	0	90	485	87	0	25	209	52	-138	-3	20	218
71: 7: 2:17:21:50	126	0	74	96	55	0	62	400	62	0	17	160	74	22	-10	14	219
71: 7: 2:17:22: 2	79	0	29	62	42	0	35	298	35	0	9	100	100	36	-16	22	220
71: 7: 2:17:22:11	82	0	48	75	37	0	39	290	35	0	9	130	65	12	-6	11	221
71: 7: 2:17:22:35	184	0	39	140	105	0	73	500	88	0	12	220	78	29	-18	15	222
71: 7: 2:17:22:55	115	0	67	94	54	0	55	402	58	0	10	154	66	9	-4	7	223
71: 7: 2:17:23:16	208	0	112	164	96	0	100	500	95	0	23	265	84	-164	-10	6	224
71: 7: 2:17:23:27	247	0	108	169	107	0	112	500	110	0	20	283	79	15	-3	45	225
71: 7: 2:17:24:39	109	0	66	78	50	0	54	322	55	0	21	136	43	-29	2	42	226
71: 7: 2:17:24:54	216	0	107	142	95	0	92	500	97	0	19	256	17	-105	-13	7	227
71: 7: 2:17:25: 7	112	0	68	84	48	0	55	335	48	0	22	148	88	1	-5	13	228
71: 7: 2:17:25:16	300	0	128	242	129	0	127	500	125	0	18	376	76	24	-16	14	229
71: 7: 2:17:25:42	127	0	65	94	50	0	62	379	55	0	13	150	90	10	-9	33	230
71: 7: 2:17:25:58	194	0	100	188	66	0	86	500	75	0	15	280	86	-158	-3	21	231
71: 7: 2:17:26: 8	85	0	44	63	39	0	39	278	43	0	18	112	49	10	-5	9	232
71: 7: 2:17:26:47	233	0	120	165	95	0	105	500	102	0	25	272	51	-217	-10	-68	233
71: 7: 2:17:27:15	163	0	81	116	73	0	75	453	75	0	13	199	53	-97	-1	9	234
71: 7: 2:17:28: 1	153	0	64	112	69	0	70	435	69	0	12	186	90	-16	-6	29	235
71: 7: 2:17:28:32	150	0	55	132	66	0	65	500	66	0	12	202	11	-9	-5	44	236
71: 7: 2:17:28:47	139	0	74	116	58	0	65	467	62	0	20	187	52	11	-6	13	237
71: 7: 2:17:29:30	100	0	42	53	50	0	44	284	54	0	16	114	72	23	-5	17	238
71: 7: 2:17:29:46	218	0	110	154	83	0	94	500	100	0	25	268	96	-10	-11	40	239
71: 7: 2:17:30: 9	86	0	49	70	32	0	39	249	39	0	12	109	72	20	-6	18	240
71: 7: 2:17:30:28	240	0	198	173	70	0	126	500	107	0	45	290	-61	-172	-7	8	241
71: 7: 2:17:30:41	301	0	107	214	125	0	132	500	126	0	25	336	65	13	-12	12	242
71: 7: 2:17:31:13	70	0	43	50	26	0	32	189	30	0	8	84	88	-8	-4	28	243
71: 7: 2:17:31:22	184	0	77	130	86	0	82	500	78	0	14	218	7	37	-8	59	244
71: 7: 2:17:31:46	81	0	50	64	30	0	35	226	34	0	10	106	65	13	-4	14	245

71: 7: 2:17:32: 1	120	0	94	89	45	0	66	341	57	0	19	154	70	-136	3	16	246
71: 7: 2:17:32:20	197	0	120	146	72	0	94	500	94	0	29	248	60	18	-2	18	247
71: 7: 2:17:32:34	147	0	117	110	56	0	80	438	73	0	35	190	10	-107	3	6	248
71: 7: 2:17:34: 4	303	0	204	240	95	0	130	500	130	0	38	398	47	-10	5	11	249
71: 7: 2:17:35:11	80	0	48	64	40	0	40	250	33	0	19	110	49	-7	4	12	250
71: 7: 2:17:35:28	150	0	38	104	70	0	68	421	62	0	11	118	101	6	-16	36	251
71: 7: 2:17:35:50	104	0	68	74	40	0	52	285	50	0	12	127	97	39	-1	31	252
71: 7: 2:17:36:36	87	0	64	66	33	0	45	247	39	0	17	114	110	1	1	7	253
71: 7: 2:17:37: 5	310	0	232	235	87	0	150	500	132	0	54	381	104	-271	14	-93	254
71: 7: 2:17:37:18	109	0	60	82	50	0	53	333	56	0	29	137	84	-11	4	29	255
71: 7: 2:17:38: 0	69	0	39	47	32	0	32	186	30	0	8	80	47	21	-2	17	256
71: 7: 2:17:38:38	87	0	75	85	25	0	43	252	40	0	18	140	81	-57	16	-6	257
71: 7: 2:17:38:56	156	0	160	145	40	0	85	450	70	0	42	240	81	-172	4	-3	258
71: 7: 2:17:39:18	185	0	108	110	80	0	91	465	85	0	28	205	51	-101	-4	19	259
71: 7: 2:17:39:32	145	0	80	103	60	0	70	405	65	0	14	175	51	7	-3	8	260
71: 7: 2:17:40:51	65	0	65	70	31	0	32	295	30	0	18	105	74	-12	10	23	261
71: 7: 2:17:41: 9	102	0	66	72	50	0	51	305	50	0	15	128	89	3	-1	16	262
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71: 7: 2:17:42:21	193	0	90	123	83	0	87	475	87	0	16	220	23	-98	-5	25	265
71: 7: 2:17:45:25	126	0	74	100	49	0	58	346	62	0	20	164	14	-156	-4	-7	266
71: 7: 2:17:45:49	45	0	24	31	20	0	21	123	18	0	11	38	44	-3	-2	5	267
71: 7: 2:17:48: 1	173	0	120	150	70	0	85	500	84	0	39	252	29	22	3	39	268